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Designing An Open-Source Power Inverter (Part 10): Converter Protection Circuits

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Recent installments in this Volksinverter article series[1-9] have discussed the design of the control power supply[8, 9] which resides in the BCV401 module. This module of the design also incorporates the battery-converter protection circuits. These include undervoltage and overvoltage protection, overtemperature protection, fan control of temperature, and overcurrent protection. This article presents and explains the operation of these protection circuits.

These circuits provide overtemperature protection (OTP) of the inverter H-bridge MOSFETs, fan control for active cooling of the Volksinverter heat sink, overvoltage protection (OVP) of the battery converter, and undervoltage protection (UVP) of all MOSFETs when supply voltages during power-on and power-off are insufficient to turn them on adequately. Undervoltage gate drive causes high MOSFET (or HEMT) on-resistance and high power dissipation, a cause of MOSFET transient overtemperature despite having current within its rated range and with heat-sink temperature too low to activate the OTP circuit. See Fig. 1.

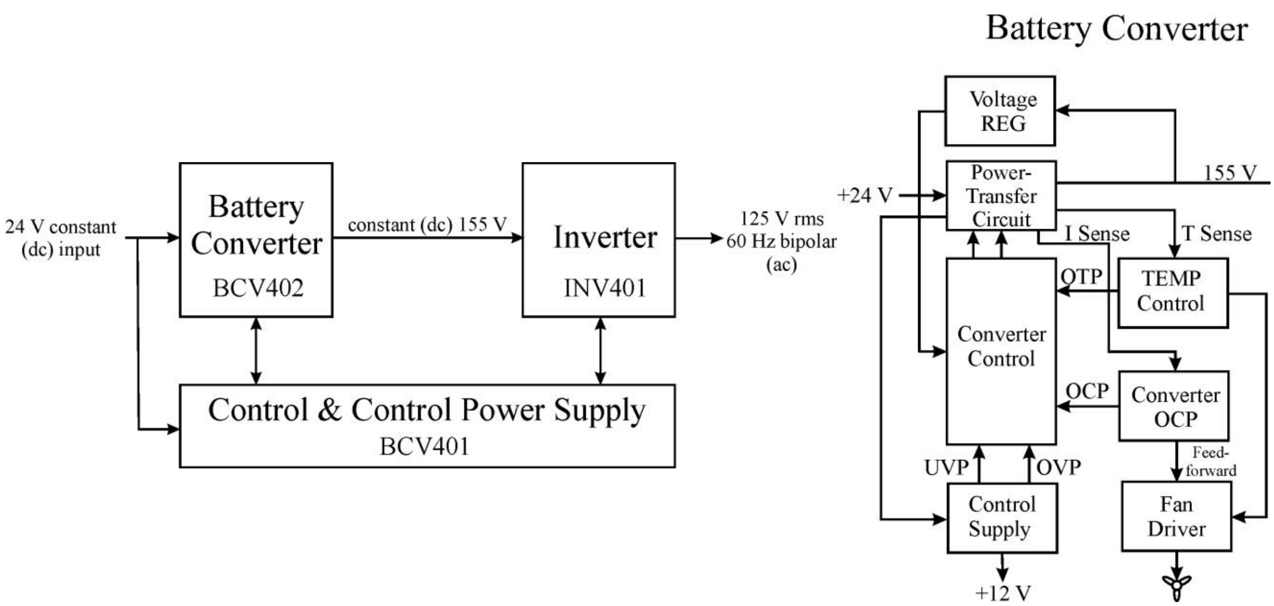

Fig. 1. The Volksinverter's control & control power supply stage, BCV401, in addition to generating control signals and the +5-V and +12-V power rails for the control circuits, also contains the protection circuits including overtemperature protection of the inverter H-bridge MOSFETs, fan control for active cooling of the Volksinverter heat sink, overvoltage protection of the battery converter, and undervoltage protection of all MOSFETs.

These circuits are essential yet do not require high performance in precision or speed. They are designed with low-cost, commodity-grade op-amps and comparators. All protection and fan control circuits have some hysteresis built in to keep them from dithering around the threshold. All of them drive the system fault bus (/FAULT) that shuts down both converter and inverter stage drivers.

Voltage Protection

Beginning at the bottom of the Fig. 2 circuit diagram, U2 is an LM339 quad comparator of the OVP, UVP, OTP and fan controller circuits. R27 of U2C (OVP) and R32 (UVP) of U2D provide positive feedback to set the voltage width of the hysteresis window. The fan controller turns the fan on at 30°C above ambient and off at 15°C. The OTP window is set for 50°C on and 20°C off above ambient, where *ambient* is the temperature of D13.

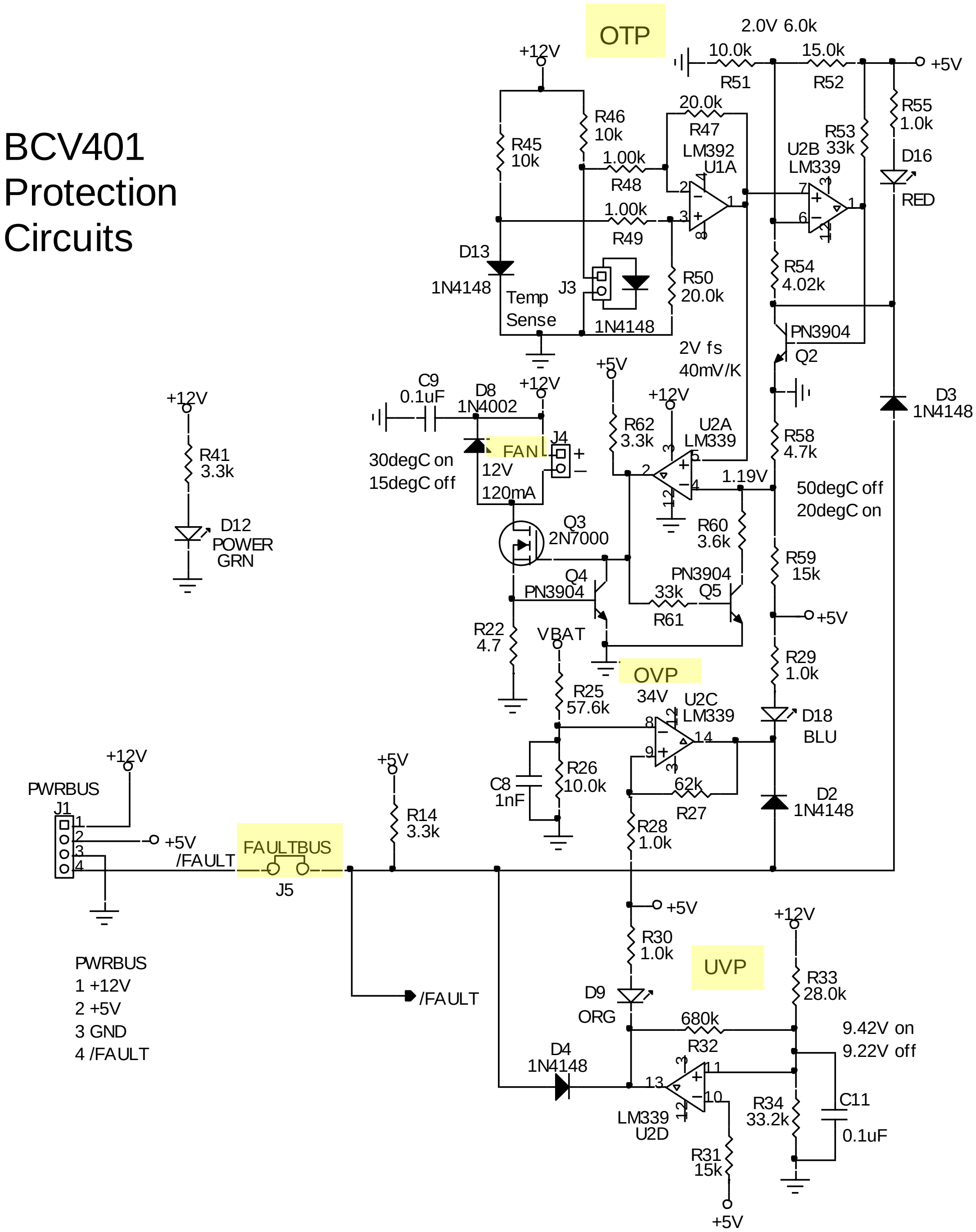

Fig. 2. BCV401 protection circuits: overtemperature (OTP) and fan control, overvoltage (OVP), and undervoltage (UVP) output to the /FAULT bus line. The converter shuts down at over 50°C, battery voltage above 30 V and 12-V control supply voltage below 9.22 V. The fan turns on at 30°C above ambient and off at 15°C. OTP similarly operates between 20°C and 50°C above ambient temperature sensed by D13.

The temperature measurement is based on the differential voltage across D13 and a sensor diode at J3—both low-cost 1N4148 diodes which need not be precision matched but preferably are taken from the same manufacturing roll. The diodes conduct about 1 mA, and their voltage difference ΔV is thus the thermal voltage $V_T = k_B \cdot T / q_e \approx$ 25.58 mV at 300 K (27°C). U1A is a one-op-amp diff-amp that has an output scale factor of 40 mV/°C with a 2-V full-scale output. U2B is a hysteretic comparator. D2 to D4 couple protection circuits to the active-low fault bus /FAULT.

The OVP hysteresis comparator (shown again in Fig. 3) output goes high when the battery voltage VBAT decreases to below the 30-V threshold. The U2C inverting (−) input is from VBAT divider R25 and R26. When the U2C output is high, the LED D18 is off, the fault bus is released (no fault), and current through R27 is zero. The voltage divider of the U2C noninverting (+) input sets the OV threshold V_{OV} at 5 V; VBAT < V_{OV} = (6.76)·(5 V) = 33.8 V. The additional 3.8 V provides a 10% margin to ensure that the inverter operates at VBAT = 30 V.

When the U2C output is low, the + input divider V_{OV} = (6.76)·(4.92 V) = 33.25 V and as VBAT decreases, the OVP fault is released at this voltage. Thus, OVP asserts when VBAT = 33.8 V and deasserts when VBAT decreases to 33.25 V, sufficiently above 30 V to provide a margin ensuring operation at 30 V but also low enough to protect drain-source breakdown of the converter power switches.

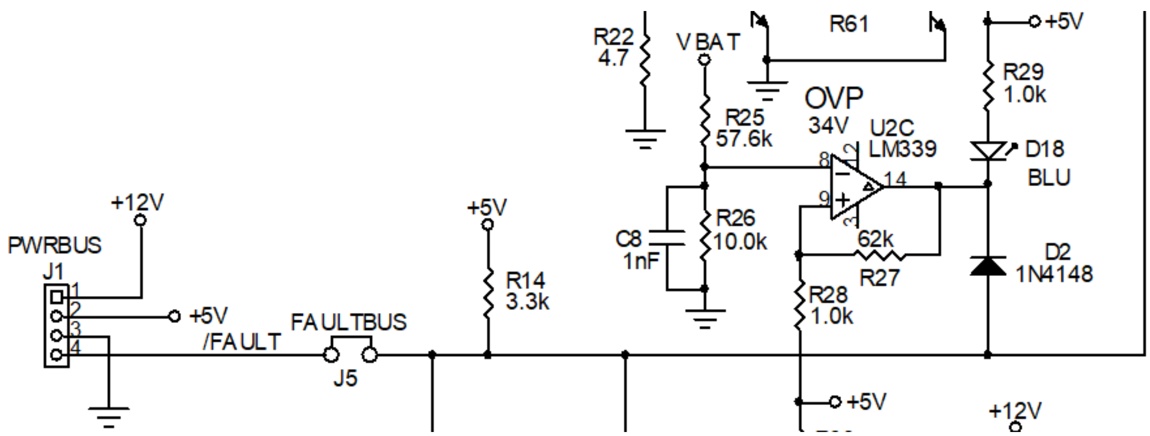

Fig. 3. The OVP circuit.

The UVP hysteresis comparator (see Fig. 4), unlike the OVP comparator, has a noninverting hysteresis loop. The two hysteresis loops are shown in Fig. 5. Undervoltage protection keeps power switches from being underdriven while the control supply (not VBAT) of a nominal 12 V is too low to drive them fully on. At power-on (or power-off) when V_{12} = +12 V is below 9.22 V, UVP is asserted on the /FAULT line and the LED D9 lit.

As power-on voltage rises to above 9.42 V, UVP deasserts and releases the /FAULT line. The V_{12} divider, R33 and R34, outputs voltage $V_{UV} = V_{12}/1.843$ with a series resistance of 15.19 kΩ. When comparator v_O is high, V_{UV} > 5 V, the LED is off, there is no current through R30 and R32, and the UVP threshold V_{UV} > (1.843)·(5 V) = 9.217 V.

In the other state, the equivalent circuit is a voltage source of $V_{UV} = V_{12}/1.885$ in series with 14.86 kΩ. When UVP is asserted and v_O is low (≈ 0 V), then V_{UV} < 5 V, /FAULT is asserted, and V_{12} < (1.885)·(5 V) = 9.423 V, the voltage at which the UVP circuit releases /FAULT. The 0.2 V window keeps the output from dithering the /FAULT line when V_{12} is near the threshold voltage.

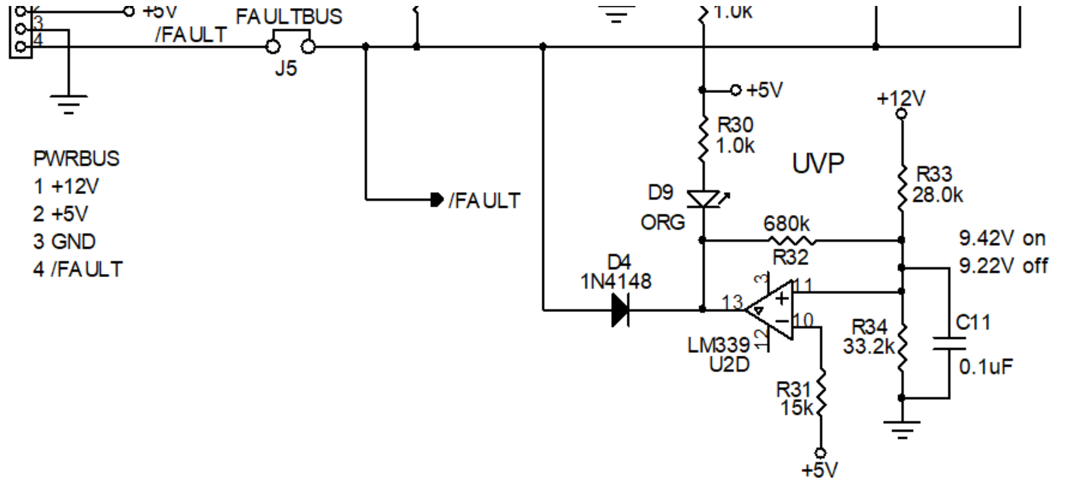

Fig. 4. The UVP circuit.

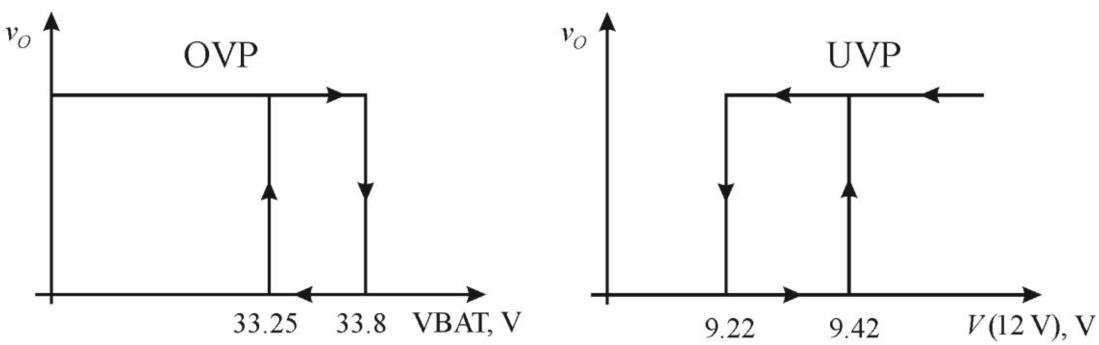

Fig. 5. The outputs of hysteretic comparators for OVP and UVP circuits. Low $v_O \Rightarrow$ /FAULT. The hysteresis window width is the difference for each circuit of the two voltages shown on the V_{BAT} axis.

Temperature Protection

Protection from high temperature, or overtemperature protection (OTP), is often based on sensing temperature with a thermistor. The sensor is attached to the case of a power switch or to the heat sink. Although thermistors are not expensive (except precision interchangeable thermistors), their R(T) curves vary significantly and are not accurate, leading to sloppy temperature protection.

In contrast, a p-n junction makes a very good temperature sensor if applied correctly. Two matched diodes—matched to the extent that they come from the same manufacturing roll—are lower in cost than a thermistor and can sense to an accuracy of around 1°C with low-cost circuits.[10]

Diodes (or any p-n junctions) have, for current I, a voltage of

$$V_D = V_T \cdot \ln\left(\frac{I}{I_S}\right), I >> I_S$$

where thermal voltage V_T and saturation (leakage) current I_S are both temperature-dependent. Combined, the junction voltage varies with temperature T around 300 K by

$$\frac{dV_D}{dT} = \frac{V_D - 1.241\,\text{V}}{T} = \frac{(0.635\,\text{V}) - 1.24\,\text{V}}{300\,\text{K}} = -1.96\,\text{mV/K} \approx -2.0\,\text{mV/K}$$

If two junctions are matched, then their $V_D(T)$ values are equal and can be compared when conducting the same amount of I. The differential voltage across the diodes is input to an amplifier as

$$V_I = V_D(T_A) - V_D(T) = V_D(T_A) - [V_D(T_A) + TC \cdot \Delta T] = -TC \cdot \Delta T \approx (+2\,\text{mV/K}) \cdot \Delta T$$

For a full-scale (fs) temperature rise above ambient temperature T_A of ΔT = 50°C = 50 K, then V_I (fs) = +100 mV. For an amplifier output at Δ50 K of 2 V fs, then the scale factor (voltage gain) is 40 mV/K with a range of 0 V at zero scale (zs) and 2 V at fs. The U1A diff-amp (see Fig. 6) thus requires a gain of

$$A_v = \frac{v_O(\text{fs})}{v_I(\text{fs})} = \frac{2\,\text{V}}{0.1\,\text{V}} = 20$$

The accuracy of this scheme depends on the diff-amp gain resistor tolerances[11] and the two currents in the diodes being equal. Ideally, they are driven by current sources, but to keep the circuit simple and cheap, resistors from the 12-V supply instead are the source.

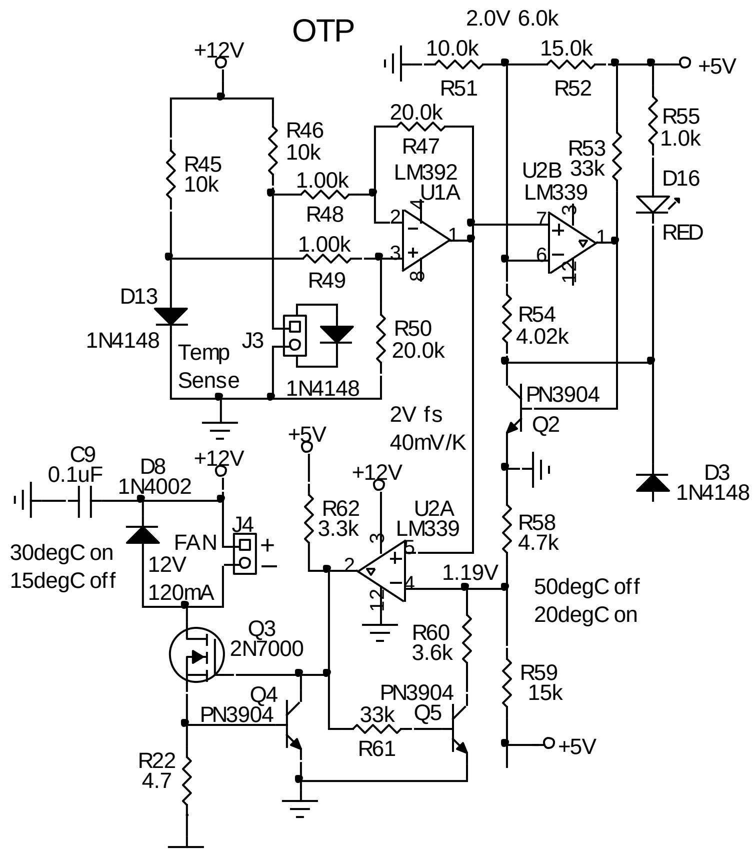

Fig 6. OTP circuit.

At ΔT = 50 K, R45 sources 1.135 mA to D13 at T_A; R46 sources 1.145 mA to the diode sensor attached to connector J3. The BJT-input op-amp U1A has an input bias current of 31 µA from R49 current at 0.653 V across D13. The noninverting op-amp input has 31 µA flowing into it; the inverting op-amp input, with feedback current included and with v_O at 2 V fs, has 69 µA flowing out of it to the sensor diode. By KCL,

$$I_{D+} = 1.135\text{ mA} - 31\text{ µA} = 1.104\text{ mA} \;\; ; \;\; I_{D-} = 1.145\text{ mA} + 69\text{ µA} = 1.214\text{ mA}$$

This difference in I_D causes a sensor voltage error of

$$V_{I\varepsilon} = V_T \cdot \ln\left(\frac{I_{D+}}{I_{D-}}\right) = -2.455\ \text{mV} \Rightarrow V_{o\varepsilon} \approx -49.1\ \text{mV}$$

This error at the output $V_{O\varepsilon}$ corresponds to a temperature error of −1.23°C.

An LM392 op-amp also has an input voltage offset error of typically 7 mV, causing the output voltage to be in error by 140 mV or 3.5°C. The diff-amp common-mode (CM) error from a finite common-mode (CM) gain A_{CM} is caused by gain-setting resistor tolerances ±1% or ε = 1% = 0.01. The CM gain error from a change in average input voltage over temperature is[2]

$$A_{CM} \approx \left(\frac{A_{v0}}{A_{v0}+1}\right) \cdot (4 \cdot \varepsilon) = \left(\frac{20}{21}\right) \cdot (0.04) = 1/26.25$$

A Δ1 K error is output if the CM (average) input voltage is varied by (40 mV/K)/26.25 = 1.52 mV. The 75-mV ripple on the +12-V supply contributes negligible (8 μV) error. Overall, a commodity op-amp is sufficient in accuracy as are batch-matched diodes.

The voltage output of U1A scales with temperature (at Δ40 mV/K above ambient) and is input to the U2B comparator. It drives Q2 and feeds back through the divider formed by R_f = R54 and by R51 || R52 driven by V_R = 5.0 V which outputs 2.0 V behind R_i = R51 || R52 = 6.0 kΩ. When this hysteretic comparator circuit is solved, the voltage thresholds for the hysteresis window are

$$V_U = V_R \cdot \frac{R_{51}}{R_{51}+R_{52}} = \frac{R_i}{R_{52}} \cdot V_R \Rightarrow R_{51} = \frac{V_U}{V_R - V_U} \cdot R_{52}$$

$$V_L = V_U \cdot \frac{R_{54}}{R_{54}+R_i} \Rightarrow R_{54} = \frac{V_L}{V_U - V_L} \cdot R_i$$

The fan controller, U2A and Q5, shares the temperature-sensed output with the OTP. MOSFET Q3 drives the fan and Q4 protects it from overcurrent during stalls and while starting. Diode D8 shunts fan motor inductive current around the windings and prevents Q3 from overvoltage. The temperature control is, like the OTP circuit, a hysteretic comparator of similar design. The following table gives 1% and 5% resistor values for each hysteresis circuit.

Table. Resistor values for hysteresis circuits in OTP and fan controller.

R in kΩ	R52	R51	R_i	R54
OTP 1%	15.0	10.0	6000	4.02
OTP 5%	10	6.8	4.048	2.7
	R59	R58		R60
Fan 1%	10.0	3.16	2.401	2.43
Fan 5%	15	4.7	3.579	3.6

Current Protection

Overcurrent protection (OCP) is based on the concepts introduced in part 5 for the inverter stage. The same three time intervals of protection are considered in the design:

1. Passive: protection by the power circuit (inductance) to limit di/dt for the 0.5 μs to 3 μs that it is required for the active OCP loop to respond and shut off the power switches.
2. Transient: active protection for a few hundred milliseconds during which time power components are increasing in temperature below the maximum acceptable temperature.
3. Steady-state: protection for the long term against overtemperature after power components are operating at an elevated temperature within an acceptable range.

OCP protection circuitry is not included in Fig. 2 but is part of converter control, shown in Fig. 7.

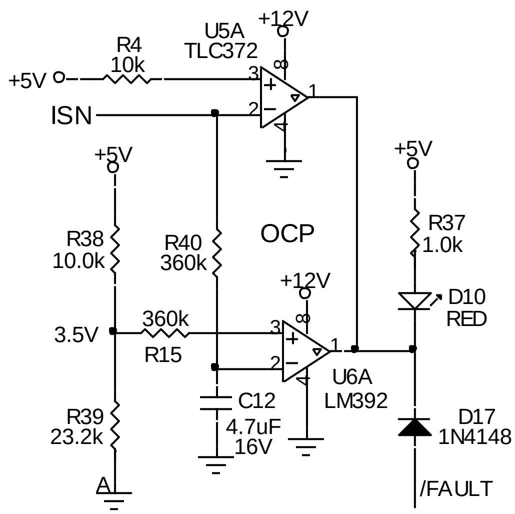

Fig. 7. BCV401 overcurrent protection circuits: U1A for transient OCP and U2A for steady-state (thermal) OCP. ISN is an input voltage scaled to the sensed power-switch current at 8 A/V.

The 5-V threshold of U5A sets a current value that protects against excessive transient current while the 3.5-V level of U6A protects at less current—the maximum steady-state value. The time-constant of R40 and C12 gives the current-sensed voltage (ISN) charging C12 at the U6A input time to increase to the 3.5-V value. This time interval is the transient protection interval during which a higher current value can be tolerated by the power switches while they increase in temperature.

In summary, five circuits protect against control undervoltage, input overvoltage, power-switch overtemperature, and transient and steady-state overcurrent. Input undervoltage is protected against in the design of the control supply. It does not begin to function until V_g > 20 V.

The design emphasis on power-switch protection also protects other power components such as the magnetic components, which have a longer thermal overtemperature time-scale and are consequently protected by protecting the power switches. Overcurrent that persists for too much time is also protected against by the input fuse as the last bastion of protection of the entire system.

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About The Author

Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

For further reading on inverter design, see the How2Power Design Guide, locate the Power Supply Function category and select "DC-AC power inverters."