Theory of Operation

Circuit: Output Voltage Clamp

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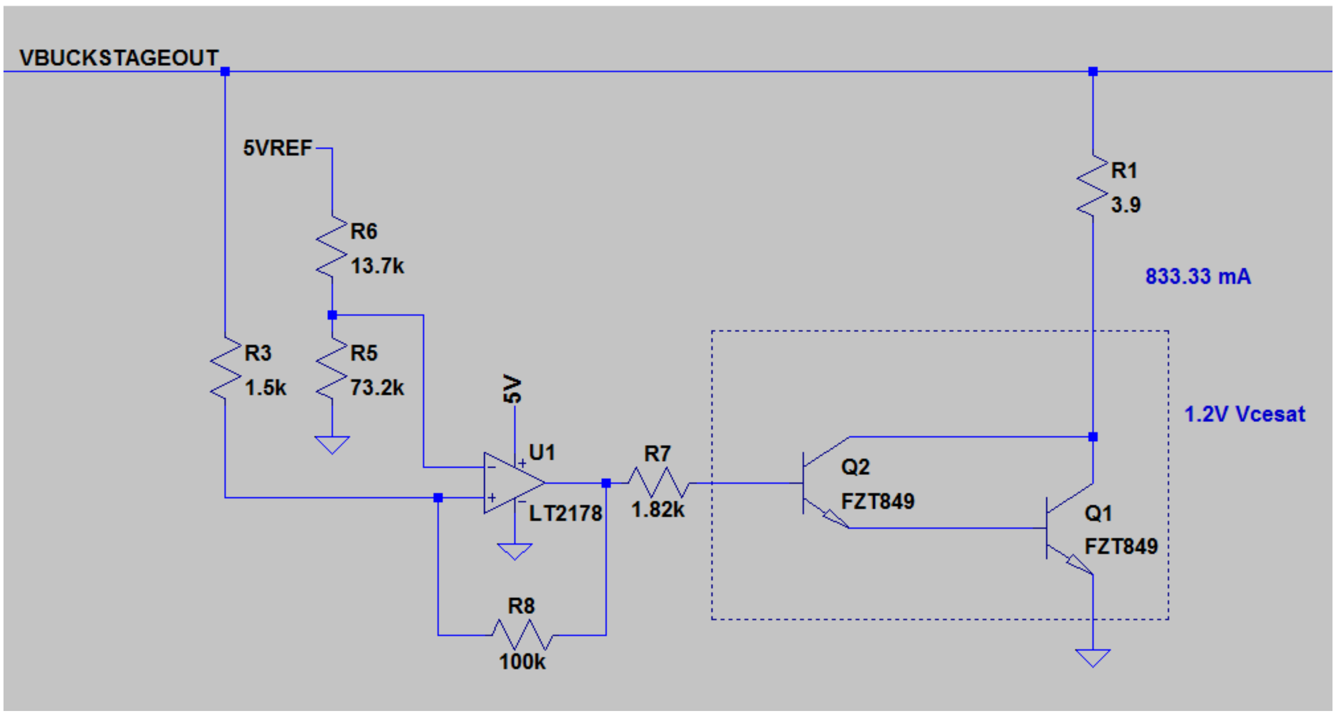

Figure 1: The output voltage clamp schematic that is intended to protect the payload from voltages above the 4.1V limit. Comparator U1 implemented with an op-amp to slow the response down. Devices shown in this schematic are for reference only.

Output Voltage Clamp Overview

The *Radio Amateur Satellite Corporation* (AMSAT) has specified that the payload will be able to withstand up to 4.3V supplied from the *Maximum Power Point Tracker* (MPPT). To ensure that the payload will not see dangerous voltages, a voltage clamp implemented with comparator U1 shown in **Figure 1** using an OPA170 op-amp driving a FZT600 Darlington pair transistor has been designed to add an additional 772 mA peak load when the voltage rises above 4.21V. The clamp will dissipate the energy as heat and then turn off once the voltage drops below 4.14V. There has been 70 mV of hysteresis added to the clamp to ensure that any extra energy has been dissipated. The 772 mA peak load was chosen to comply with NASA derating.

An example event causing a voltage spike on the output of the buck converter would be when the maximum power is applied to the load followed by the load being instantly removed. Op-amp U1 detects high voltages and drives Q1 and Q2 to dissipate the extra energy through R1 from the collapsing inductor magnetic field. The *Pulse-Width Modulator* (PWM) in the UC2524 will be forced to a 0% duty cycle when the output voltage rises to 4.1V by the output voltage “soft” PWM limit in an effort to limit the energy reaching the output, causing the voltage to be reduced. Since the only energy that is being added to the output of the MPPT after the PWM turns off would be from the collapsing magnetic field of the buck converter inductor, it is assumed that this is the only energy that will need to be dissipated. Therefore, the calculations below show the maximum amount of voltage and current that the MPPT could see with an output of 7.24W assuming ideal components and no DC/DC conversion loss. It is also assumed that all energy stored in the inductor must be dissipated.

Output Voltage Clamp Operation

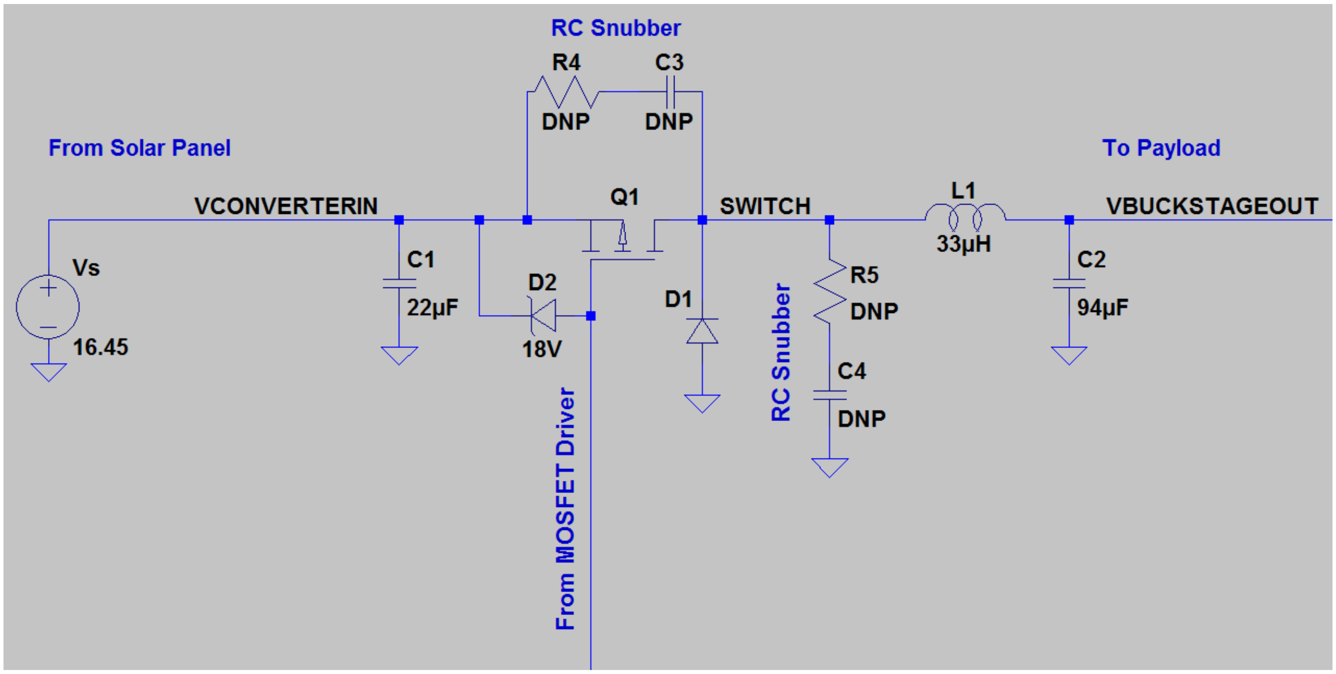

Figure 2: The DC/DC buck converter that provides energy to the output of the MPPT. Used for reference only.

$V_{BUCKSTAGEOUT}$	3.3 V
$I_{INDUCTOR}$	2.2 A
L	33 µH
$R_{CLAMPTOTAL}$	5.45Ω
P_{OUTPUT}	7.24W

Table 1: Circuit parameters at time of instantaneous load removal.

The energy stored in inductor L1 shown in **Figure 2** when the load is drawing 7.24W from the MPPT is calculated as shown:

$$E=\frac{1}{2}\cdot L\cdot I^2=\frac{1}{2}\cdot(33\,uH)\cdot(2.2\text{A})^2=79.86\,\mu J \quad \textbf{(1)}$$

The inductor attempts to maintain a constant current when the load is removed. The magnetic field will collapse and release its energy into the MPPT output node as calculated in **Equation 1**. This will cause a voltage spike that must be dissipated quickly. The OPA170 is able to source up to 10 mA into the base of the FZT600, which has a minimum gain of 1000, resulting in the clamp turning on very quickly. Once the energy is dissipated, the voltage will be reduced, and the clamp will turn off.

The voltage drop across the collector to emitter of the Darlington pair is about 1.2V worst-case which means that the peak current through the clamp will be:

$$I_{\text{Peak}}=\frac{V_{\text{BUCKSTAGEOUT}}-V_{CE}}{R_1}=\frac{4.21\text{V}-1.2\text{V}}{3.9\Omega}=772\text{mA} \tag{2}$$

The L/R time constant of the buck converter inductor and the effective clamp resistance can be calculated as shown in **Equation 3**. The inductor E*quivalent Series Resistance* (ESR) is about 50 mΩ and the effective resistance of the clamp circuit at 772 mA is 5.45Ω:

$$\tau=\frac{L}{R}=\frac{33\,uH}{5.45\Omega}=6.055\,\mu s \tag{3}$$

Equation 3 calculated the time constant of the circuit. It can be assumed that the inductor will be fully discharged after five time constants:

$$5\cdot\tau=5\cdot 6.055\,us=30.275\,\mu s \tag{4}$$

The peak power calculated in **Equation 1** will be added to the VBUCKSTAGEOUT node over the five time constants as shown in **Equation 4**. The peak instantaneous power can then be calculated:

$$P_{PEAK}=\frac{E}{\Delta T}=\frac{79.86\,\mu J}{30.275\,\mu s}=2.638\,W \tag{5}$$

A Watt is defined as one Joule per second, and components are rated in average power, meaning that average power is the energy dissipated over one second of time. This means that the average power dissipated by the 3.9 Ω resistor and Darlington transistor over one second is:

$$P_{AVG}=\frac{P_{PEAK}\cdot\Delta T}{T}=\frac{E}{T}=79.86\frac{\mu J}{1\text{ s}}=79.86\,\mu W \tag{6}$$

While the peak power dissipated by the clamp is relatively high, as observed in **Equation 5**, the average power that is dissipated (resulting in heat) turns out to be very small as calculated in **Equation 6** which assumes that the clamping action is not initiated more than once per second. It can be assumed with reasonable confidence that the unique event which causes the voltage spike will not occur often. If it is assumed that the clamp will be activated ten times per second (10 Hz) for example, **Equation 7** shows that the clamp will generate the heat equivalent of:

$$10\cdot P_{AVG}=10\cdot 79.86\,\mu W=798.6\,\mu W \tag{7}$$

Knowing that less than one milliWatt of heat is generated at 10 Hz clamping, even clamp activation at 100 Hz would be well withing the ability of the clamp components' power rating. The components used to dissipate the extra energy stored in the buck converter inductor can be very small devices, saving board space.