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Characteristics of the long duration pulses in a shunt linear voltage regulator ☆

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ABSTRACT

Shunt linear voltage regulators are still used in situations where other kinds of regulators are not advised. This paper explores a mechanism liable to induce long duration pulses (~ 100 μs) in these devices, which is eventually demonstrated using a pulsed laser facility. Data issued from these tests helps to understand how the electrical network parameters as well as the non-idealities of the devices affect the characteristics of the transients. Finally, this phenomenon is investigated in similar structures with identical purpose.

1. Introduction

The family of linear voltage regulators (or simply references, if the device is not designed to provide a high output current) is classically divided into two large subfamilies: series and shunt regulators. The second family, on which this work focusses, are devices that set an accurate voltage value in a specific node of the circuit working *in parallel* with the load. It is recommended for low power systems, also if the power supply is higher than 40 V, and, finally, is useful when negative, limiting or floating references are required [1]. A typical example is the Zener diode (Fig. 1a). The Zener diode sets the output near its breakdown voltage, V_Z. Thus, the power supply provides a constant quiescent current, $I_S \approx (V_{CC}-V_Z)/R_S$, independent of the load characteristics. The excess of current, $I_P = I_S - I_O > 0$, is drained by the diode. However, in case of needing an accurate value of the output voltage, the simple Zener diode must be discarded in benefit of structures such as that shown in Fig. 1b. In this case, an operational amplifier (op amp) sets the output voltage to $(1+k)\cdot V_{REF}$. Typically, V_{REF} is the output of a band-gap cell, a Zener diode, etc. Another function of the op amp is biasing the base of a PNP bipolar transistor to drain the excess of current. A PMOS transistor can replace the PNP one [2] as well as an NPN or NMOS transistor [3]. In this case, the op amp inputs must swap their roles to avoid positive feedback.

Voltage regulators have been tested in radiation environments investigating the effects of the accumulated damage or single event effects, as a recent review paper has summarised [4], to be used in harsh environments such as space or accelerators [5–7]. In particular, shunt linear voltage regulators have been tested in radiation facilities, sometimes focussing on total ionising dose [8–11], sometimes on the single event transients (SETs) in these devices [3,12,13]. A recent paper [3] has investigated the characteristics of the SETs in a COTS (Commercial-off the shelf) shunt regulator, the LM4050, and successfully associated the transient duration with the dynamical parameters. Unlike the *series* linear voltage regulators, the influence of the external configuration devices on the transients of *shunt* regulators has not deeply studied. A common practice is to add a bypass capacitor to the output of the voltage regulator (C_L in Fig. 1a, b) with several purposes: removal of high-frequency noise, stabilisation of the circuits, reservoir of current, etc. Other papers have shown that, contrary to the first impression, this extra device can make the transients more dangerous in *series* linear regulators [14,15]. In shunt regulators, long duration pulses (LDPs) might occur due to a similar mechanism: let us suppose that, due to the impact of an energetic heavy ion, a negative transient appears at the output of the op amp, called SENSE in Fig. 1b. As the transistor is in common-collector configuration, the output voltage, V_O tries to

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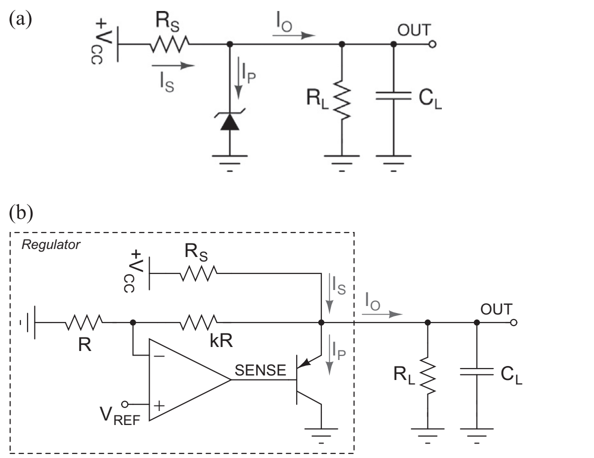

Fig. 1. Several kinds of shunt linear voltage regulators: a simple Zener diode (a) and a more accurate version based on an op amp (b).

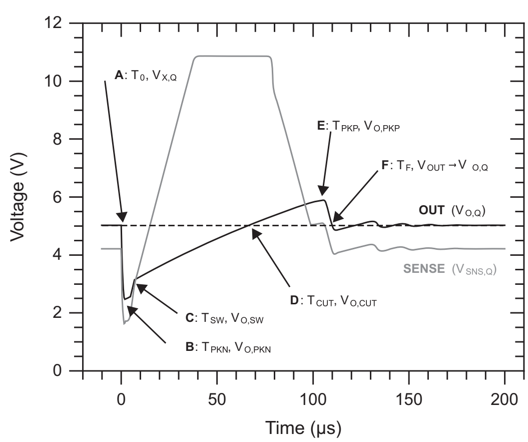

Fig. 2. Predicted behaviour of a long duration pulse in shunt voltage regulators. After the transient trigger (*A*), the OUT and SENSE voltages reach the minimum (*B*). However, due to the fact that $V_+ - V_- > 0$, the SENSE voltage, V_{SNS}, goes to the positive saturation voltage switching off the transistor in such a way that the capacitor recovery becomes that of a typical RC network (*C*). Much later, the output voltage goes beyond the DC value (*D*), $V_+ - V_- < 0$ so the op amp returns to the linear zone. Meanwhile, the output voltage goes on increasing and reaches a top peak value (*E*) before returning to the DC output voltage (*F*).

follow the evolution of V_{SNS} so a negative peak occurs at the regulator output. Then, the op amp quickly reacts since $V_- = V_O(t)/(1+k) < V_+ = V_{REF}$, quitting the linear zone and jumping to positive saturation.

If the capacitor were not present, the transient would vanish after a few microseconds since, in its trip to the positive saturation state, the output of the op amp grows so much that $V_- > V_+$. Negative feedback acts so the output voltage starts decreasing and softly returns to the stable DC value. However, the presence of the capacitor, which was efficiently discharged by the transistor but can be charged again only by I_S, freezes the output voltage so the op amp eventually reaches the positive saturation state. Then, the transistor stays cut off and the circuit behaves like a classical RC network. Fig. 2 shows the expected behaviour of the transients according to a SPICE simulation and explains why these transients are so long and intrinsically bipolar. Also, characteristic times and voltages are defined therein. This transient was simulated injecting 3 pC in a transistor, called Q09, inside the op amp gain stage. More details about the simulation can be found in Section 3.

This phenomenon is just a modification of the "peak detector effect", observed in series linear voltage regulators and references [14,15]. Some characteristics of the transients can be easily deduced. First of all, when the pass transistor goes to the OFF state, the network becomes a typical RC network (from *C* to *E* in Fig. 2). Calling $V_{O,SW} \equiv V_O(t = T_{SW})$ (*C* in Fig. 2), the final value would be

$$V_O(t \to \infty) = V_\infty = \frac{R_L^*}{R_L^* + R_S} \cdot V_{CC} \tag{1}$$

R_L^* being $R_L//[(1+k)\cdot R]$. Then, the temporal evolution is

$$V_O(t) = V_\infty + [V_{O,SW} - V_\infty] \cdot \exp\left(-\frac{t - T_{SW}}{\tau}\right) \tag{2}$$

with

$$\tau = (R_L^* // R_S) \cdot C_L. \tag{3}$$

From now on, τ will be called "*theoretical discharge time*". Finally, another interesting characteristic of the transients is the size of the negative peak, $V_{O,PKN}$. A simple way to determine the parameters that affect the value of this parameter is the following. Once the transient starts, the external PNP/PMOS transistor is set on a low-impedance state. Let us suppose that the transistor collector/drain current is limited to $I_{P,MAX}$ due to non-ideal effects such as collector/drain resistance, base resistance, and high current injection. If the transient reaches its lowest value at $t = T_{PKN}$ and provided that the transistor is discharging a capacitor, it is very easy to deduce that

$$|V_{O,PKN} - V_{O,Q}| \approx C_L^{-1} \cdot T_{PKN} \cdot I_{P,MAX}. \tag{4}$$

In other words, the negative peak transient should be inversely proportional to the capacitor value. A similar conclusion, using more sophisticated models, was deduced and experimentally observed in series linear regulators [15].

2. Experimental set-up

In order to verify that the hypothetical LDPs actually occur in shunt linear voltage regulators, the network in Fig. 1b was built using an LM124A, the behaviour of which is well known, as its core. This amplifier was fed back with a 2N2907A PNP transistor and resistors of 100 and 33 kΩ (DC gain ≈ 4). The rest of parameters was variable (Table 1). In the second round of experiments, the PNP transistor was replaced by a BS250, a silicon DMOS-PFET for high-speed switching applications. Unlike typical integrated shunt regulators, the op amp was biased by the power supply and not by its own output. Otherwise, the structure would not have worked.

Heavy-ion facilities have been traditionally the place where electronic devices are tested for SET sensitivity. However, it is widely accepted that a pulsed laser is a good tool to test bipolar technologies since the elements are much bigger than the typical spot size [16]. The possible LDPs associated with the shunt voltage regulators were investigated at the UCM laser facility [17]. In this facility, a 60-fs pulsed laser was used to induce SETs in the op amp. Its wavelength was set to 800 nm (spot size ~ 1 μm) and the energy to 60 pJ (absorption coefficient ~ 0.085 μm^{-1}, penetration depth ~ 11.8 μm [16]). It is interesting to correlate this energy with the equivalent LET of an ion. In 2000, a work by McMorrow [18]

Table 1
Top and bottom values of the circuit parameters.

Parameter	Bottom	Top
V_{REF}	0.75 V	1.50 V
V_O	3.0 V	6.0 V
V_{CC}	10 V	16 V
R_S	220 Ω	390 Ω
R_L	680 Ω	2.7 kΩ
C_L	220 nF	4.7 μF