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Precision Circuit Calculations in Hostile Environments

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Sensing and calculating electronic systems with stringent accuracy requirements use internal standard voltages for references. Conceptually, this is related to using some unit measurement for counting any quantity. The high precision electronic components used in systems in the nation's stockpile also make use of these standard voltages.

The need for stable voltage references has been long-standing in the overall electronics industry. For many applications, the most pressing need is for stability of a reference voltage as the circuit temperature varies. Typical circuit components have temperature coefficients for their operational characteristics that are given in some delta per degree centigrade and these coefficients can be either positive or negative. Therefore, it is natural to consider building a circuit out of components that have complementary temperature coefficients so that the operating characteristics of the circuit have a net zero temperature coefficient. This is the fundamental basis of precision voltage reference (PVR) circuit operation and it is straightforward to extend this type of stabilization to reduce shifts caused by hostile environment radiation.

In some stockpile applications, the requirements for stability of the voltage reference (V_{ref}) are unusually demanding for analog electronic components. These requirements make this class of circuits interesting to study with simulations to illuminate the mechanisms that provide challenge to the stability of V_{ref}. The topology of these circuits compound the challenge since the PVR circuit is coupled to a separate amplifier that is often built with a different semiconductor technology. Modeling such an amplifier in hostile environments can mean that additional radiation physics models are required.

Hostile environment simulations of PVR circuits are underway at Sandia National Laboratories (SNL) with funding from the Nuclear Survivability Engineering Campaign and the Advanced Simulation and Computing (ASC) Program. The simulations generate

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information to be used in design and qualification of systems using these circuits. This report describes the operation of a generic PVR circuit and the challenges involved with these simulations.

In order to study the abilities of this circuit to cope with fluctuations, it is necessary to understand how the circuit design maintains a constant V_{ref}. This type of circuit is a Brokaw circuit[i] which is a type of stabilized band gap voltage circuit. The design of the circuit is optimized for stability under temperature excursions[ii] and is based on transistor characteristics well-behaved with temperature. [iii] The circuit is modified with an additional resistor to provide stability against radiation induced changes. Figure 1 displays a schematic of a PVR circuit.

The principle components of a band gap circuit are two current paths incorporating resistors so that two current dependent voltages are generated. The two current paths also include circuit elements such as diodes or transistors that control the current as a function of applied voltage (V_A). Refer to Figure 2 for a graph representing these currents.

The two current paths are designed so that the two controlling circuit elements regulate the currents in each path at different rates with respect to the controlling voltage. In addition, these circuit elements are designed to provide different currents at some initial low V_A. In this way, one of the circuit elements (call it Q1) with a higher initial current at low voltages can be constrained to increase its current with applied voltage at a slower rate than the other circuit element (call it Q2). Q2 has a lower initial current at low applied voltages and a faster rate of current increase with applied voltage. It can be forced to pass an identical current as Q1 at some applied voltage. As the applied voltage is increased from low to high, the two current paths start with unequal currents that converge at some applied voltage and then diverge as the applied voltage is further increased.

The currents through Q1 and Q2 are monitored by the generated voltages at the resistors in the current paths. The behavior of these monitor voltages (V_{C1mon} corresponds to Q1 and V_{C2mon} corresponds to Q2) is similar to the currents as a function of the applied controlling voltage. At the applied voltage (call it V_{bg}) where the currents are equal, $V_{C1mon} = V_{C2mon}$. At all other values of the controlling voltage, the monitor voltages are unequal and $V_{C1} < V_{C2}$ for $V_A < V_{bg}$ and $V_{C1} > V_{C2}$ for $V_A > V_{bg}$. This polarity reversal at V_{bg} is sensed by an operational amplifier and used to control the band gap circuit by influencing the applied voltage to the circuit elements Q1, Q2. This operational amplifier can be configured so that the net applied voltage is forced to the V_{bg} voltage where the currents are equal. V_{bg} is related to the circuit precision output voltage V_{ref} through a resistor.

The challenge of modeling this circuit setup in radiation environments is to model the normal operation of the circuit to 1% error or less (including temperature effects) and also the effects of radiation on the transistors (Q1, Q2) within the PVR circuit as well as radiation effects to the operational amplifier. Ongoing work at SNL using an ASC simulation code Xyce, is directed towards constructing high accuracy simulations of the transistors that include transistor physical degradations arising from displacement damage caused by neutron or heavy ion radiation.

The displacement damage radiation effects reduce the Q1 and Q2 currents but not equally. In this way, the intersecting voltage where the currents are equal varies slightly and this variation leads to instabilities in the output V_{ref} voltage since V_{ref} is related to V_{bg}. The radiation modeling of this circuit effect must account for different radiation responses between Q1 and Q2 that may vary stochastically. This stochastic response is due to the radiation-caused generation of defects and may be non-uniform in small devices. The radiation response calculations are based on computations of defect induced recombination currents and increases in device resistivities as a function of defect densities.

In typical simulations, the radiation responses of the Q1 and Q2 transistors are varied independently to reflect the experimentally known result that neutron damage in small transistors is variable. This leads to V_{ref} shifts to both higher and lower voltages than the pre radiation voltage. It is of interest to model these effects in an ensemble of circuits rather than individual circuits so uncertainties are included for the phenomena being simulated. This treatment of the damage uncertainty yields a distribution of shifts that can be compared to similar distributions compiled from experiment.

The Xyce code also includes models to replicate the additional charge introduced in some transistors by ionizing radiation. This dose rate dependent radiation model utilizes device geometry information to calculate total generated charge. This charge results in voltage offsets within the operational amplifier associated with photo-currents and also causes time-dependent current surges between the PVR and the operational amplifier.

These voltage offsets are transient and depend on the configuration of devices in the operational amplifier circuit. These in turn will influence the operational amplifier output voltage and this affects the controlling voltage of the PVR. These transient effects introduce further variation into the value of V_{bg} and thus V_{ref}.

Although the PVR simulations are still under refinement, the results to date indicate good fidelity with measured data of these circuits in radiation environments. More work is planned to further develop the physical degradation models and to complete the calculations with relevant uncertainties that will enable a calculation of circuit performance margin with respect to requirements.

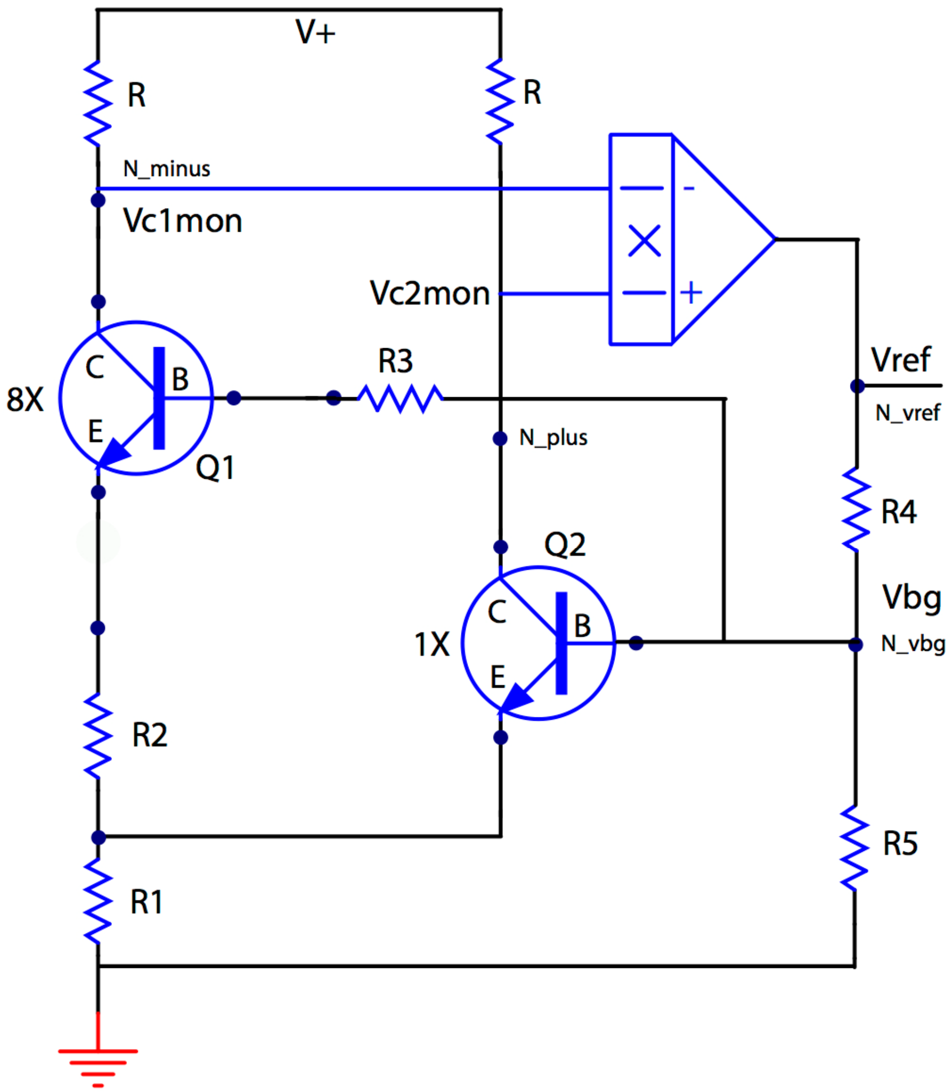

Figure 1. A simplified schematic of the Brokaw based band gap reference circuit. Currents in the two transistors Q1 and Q2 are forced to be equal by the external op-amp. V_{bg} is the generated band gap output voltage and V_{ref} is the higher-by-design reference output voltage.

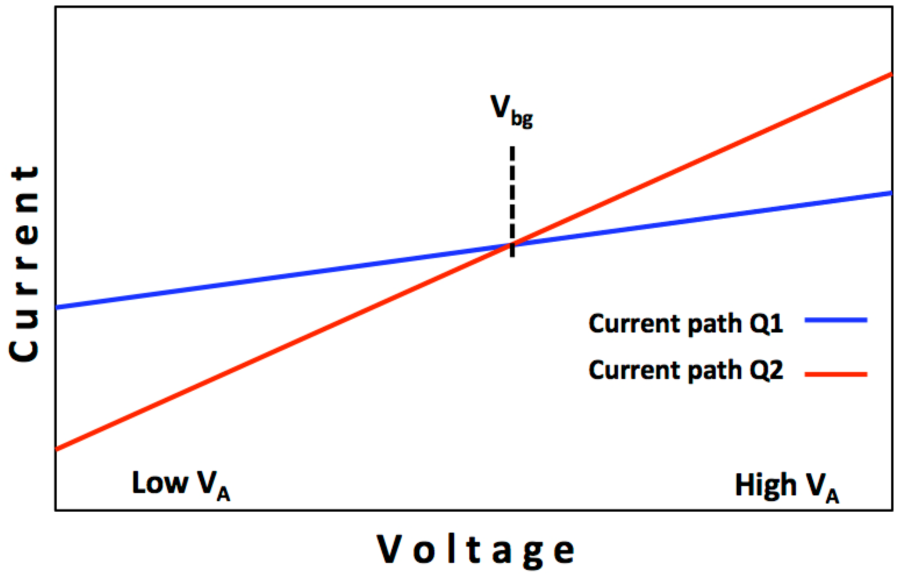

Figure 2. Two currents flowing in two current paths in a hypothetical bandgap circuit.

[i] A. P. Brokaw, A Simple Three-Terminal IC Bandgap Reference, *IEEE Journal of Solid-State Circuits,* SC-9(6):388–393, Dec. 1974.

[ii] R. J. Widlar, New Developments in IC Voltage Regulators, *IEEE Journal of Solid-State Circuits*, SC-6(1):2–7, Feb. 1971.

[iii] J. S. Brugler, Silicon Transistor Biasing for Linear Collector Current Temperature Dependence, *IEEE Journal of Solid-State Circuits,* SC-2(1):57–58, Jun. 1967.