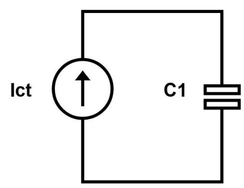
Using a Constant Current Source (CCS) to charge a capacitor

Theoretical write-up

I want to build a ramp waveform generator for voltage sweeping in test circuitry. This is the first step.

The underlying principle is simple: Push a constant current through a capacitor to charge is such a way that V t is a linear relationship.



Basic idea of CCS charging

The relationship between charging time, current and capacitance can be derived as follows:

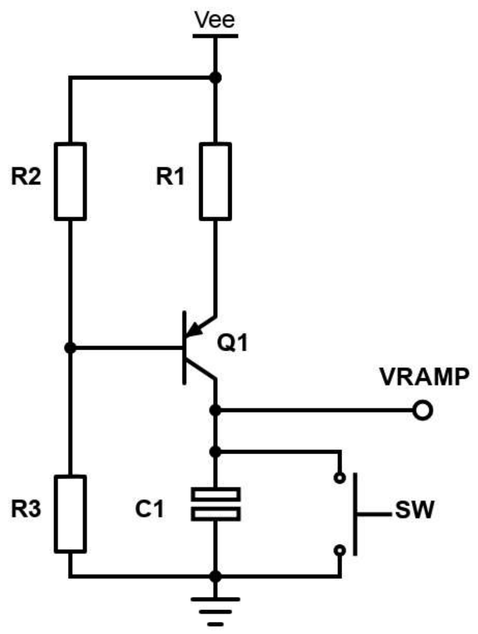
$$Q(t) = C \cdot V(t)$$

$$Q(t) = I(t) \cdot t$$

$$I(t) \cdot t = C \cdot V(t)$$

$$V(t) = \frac{1}{C} \cdot I_{ct} \cdot t$$

As the capacitance and current are taken to be constant, we observe that the resulting equation is linear. One limitation is the fact that the current source will only function as long as a certain voltage is maintained across itself. After a certain point the voltage at the positive end of the capacitor will have risen enough to impede the proper functioning of the CCS. The switching of the ramp should occur before we lose linearity.



Basic tipology of Ramp generator

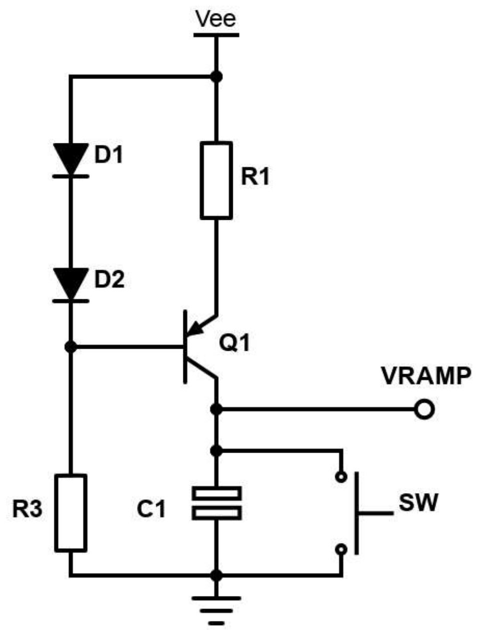
The circuit from above acts as a CCS if $V_{CE} > V_{BE}$ and the current flowing is determined by this formula:

$$I_E = \frac{V_{EE} \cdot \left(1 - \frac{R3}{R2+R3}\right) - V_{EB}}{R1}$$

V_{EB} is not constant and varies with collector current and with temperature, which is evident if we write V_{BE} as a function of I_B : $V_{BE} = n\frac{K_B T}{q} \cdot ln\left(\frac{I_C}{I_S(T)}\right)$

To meaningfully adjust the emitter current we exchange the emitter resistor for a potentiometer. The time the voltage takes to raise to the max is inversely proportional to the current.

To counteract the effects of thermal variation we can replace $R2$ with two diodes, one to counteract the thermal variation of V_{BE} and the other to set the value of the current, as it can be understood from the formula:
$I_E = \frac{V_{D1}(T)+V_{D2}(T)-V_{EB}(T)}{R1}$, where $V_{D1} \approx V_{EB}$ and so the current in the circuit has the formula:
$I_E = \frac{V_{D2}}{R1}$

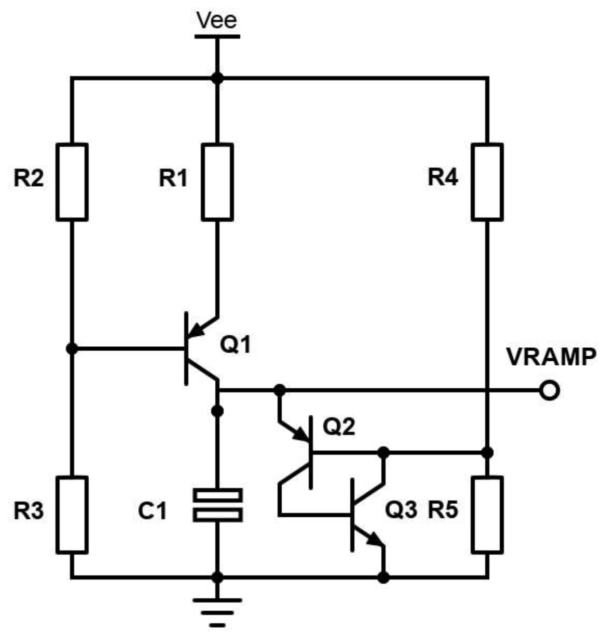


Diode compensated CCS with lower collector current

We can use any type of CCS when trying to charge the capacitor.

A true ramp generator should have a periodic output signal and since man can't flick the switch open and close 1000s of times per second we need to use a voltage or current controlled switch across the capacitor to periodically discharge the capacitor.

We can also use a local oscillator and build a circuit like the one below with only three transistors needed:



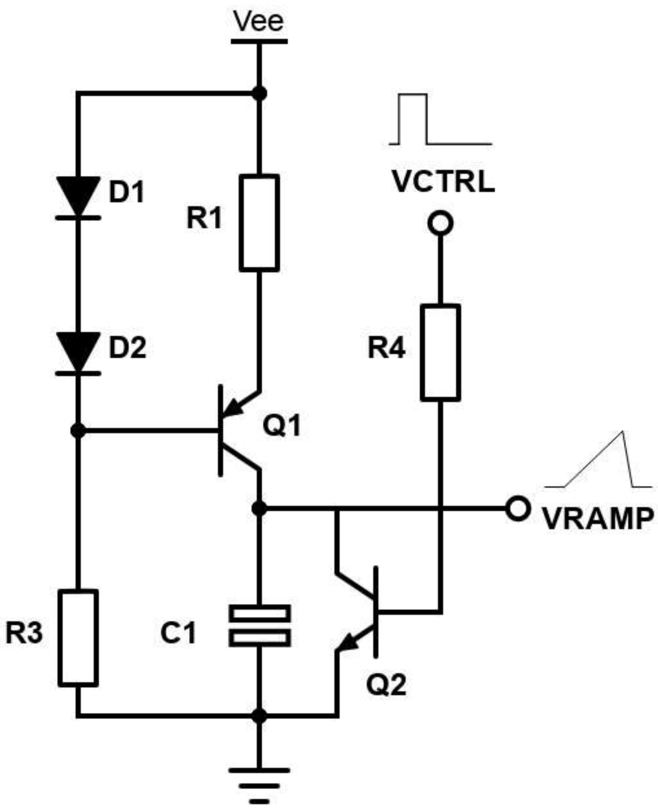
Three-transistor Ramp Generator w/ local oscillator

The PNP/NPN complementary pair is electrically equivalent to a thyristor, a type of semiconductor voltage controlled rectifier.

Demonstration

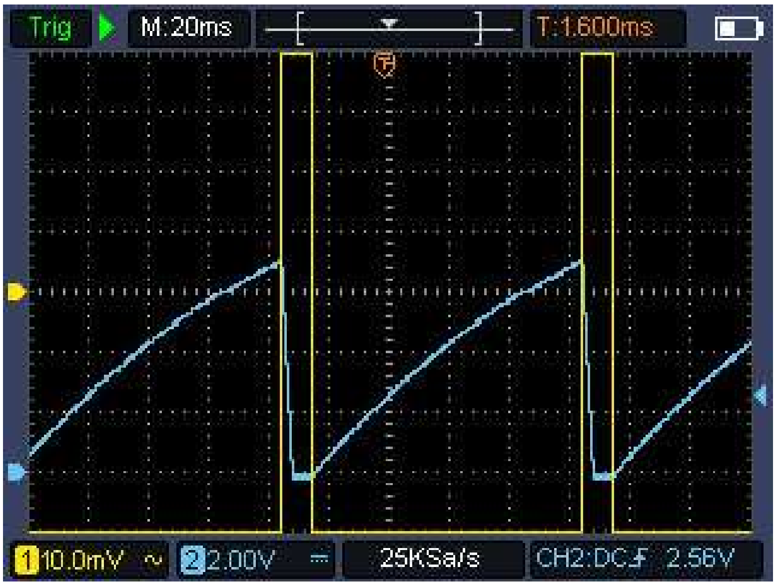
Experiment No.1 used the circuit typology presented earlier with the added feature of a voltage-controlled bipolar transistor as a switch. I used a BJT because I didn't have a function generator that could provide higher-than-threshold voltages to a regular MOSFET.

The diodes D1 and D2 were used in order to obtain a lower constant current and so increase the charge time of the capacitor.



Breadboarded circuit of the Ramp Generator

It is very important that we do not overextend the ramp's duration, as too long of a ramp will present noted non-linearities. This can be seen in the image below, where current was decreased too much.

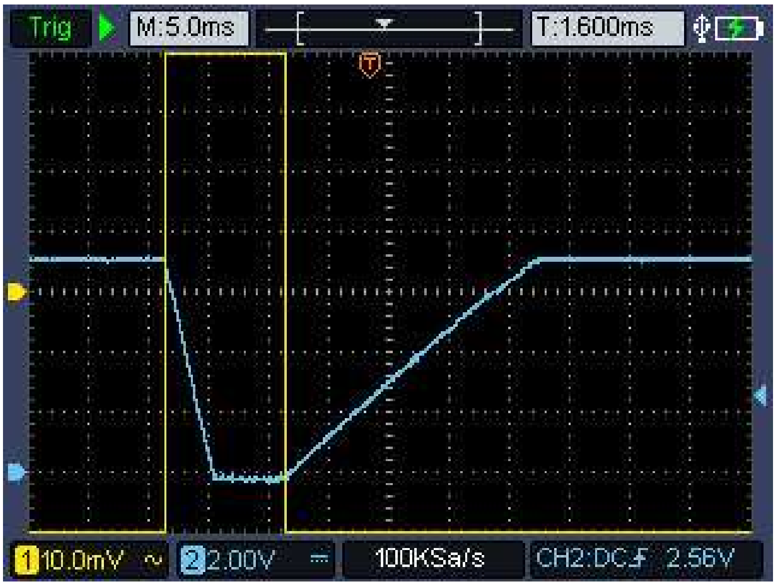


Degradation of linearity in ramp waveform

The control signal of the second bipolar transistor needs to have its duty cycle altered depending on the charge time of the ramp. This is done in order to prevent both nonlinearities in the charging curve caused by degrading the current regulation capability of the CCS, as well as to include or exclude voltage plateaus.

Voltage plateaus can be useful when the component being tested dissipates a lot of heat as turning off the DUT from time to time "averages" out the termal effects.

In the figure below I present a properly linear ramp generated by the test-circuit.

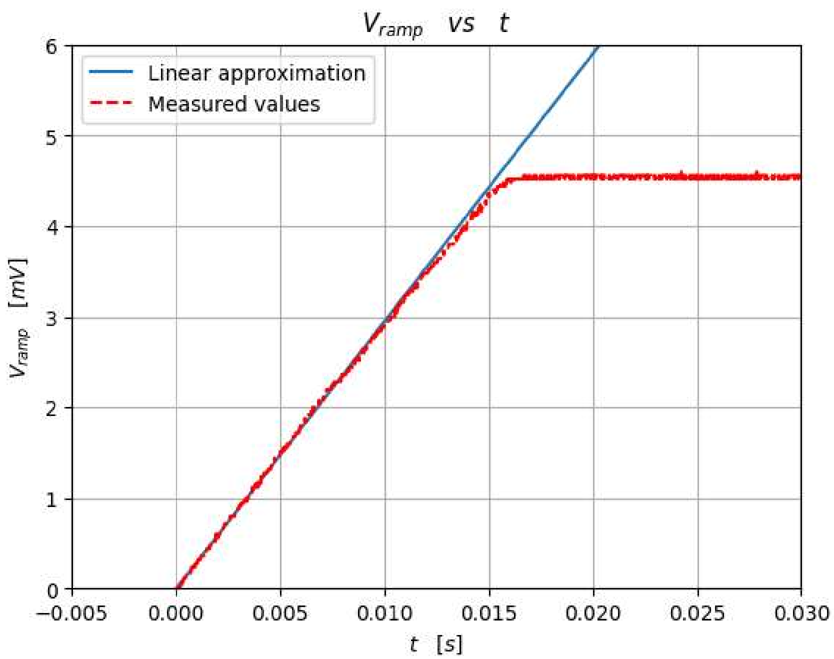


Adequately linear ramp waveform

Testing for Linearity

After we extract the values from the oscilloscope storage we select the range of points that make up the linear part of the waveform. We apply linear interpolation and obtain a linear equation of the type $slope \cdot t + yIntercept$. It might seem worrying that besides the obvious slope we have an added offset, but this is resolved by dragging the waveform to the left such that the y intercept becomes zero.

We express the voltage across the capacitor as $V(t) = \frac{I_{ct}}{C} \cdot t$, so the slope of the graphed curve is $\frac{I_{ct}}{C}$. When we compare the linear approximation to the measured waveform we see, as shown below, that the approximation is quite accurate.



Comparison between measured values and linear approximation

Conclusions

- It took a lot of tweaking to obtain proper results, but hey it's cheaper than a function generator
- Still have to find a way to discharge the capacitor into a MOSFET or another semiconductor component
- Monitoring current will be a big challenge in building IV characteristics with test-circuits like this

Resources

- [Similar Stackexchange question that I found after working on this project]
- [Building PUJT or SCRs from bipolar transistors for local oscillator]