Switched capacitor circuits

Problem: Large C can take a lot of chip area \( \rightarrow \) use \( C < 1 \mu F \)
but need \( RC = 10^{-3} \) so \( R = 10^{8} \) which is also to large for a chip.

Solution: replace \( R \) with switched \( C \)

\[
\begin{align*}
Q &= \text{Vamp} \\
\text{Ain} &= \text{Cin Vin when switch to Vin}
\end{align*}
\]

When switch to Vamp, \( \text{Ain} \) goes to \( C_f \) and \( \text{Cin} \) discharges completely because \( \text{Vamp} = 0 \).

\[
\text{I}_{Aav} = \frac{\Delta Q}{\Delta t} = \text{Ain Fcloc} = \text{Cin Vin Fcloc}
\]

Equivalent resistance \( \text{R}_{eq} = \frac{1}{\text{Cin Fcloc}} \)

Note smaller \( \text{Cin} \) \( \rightarrow \) larger \( \text{R}_{eq} \)

Fcloc must be more than twice as high as any frequency in the signal.

- This is fine. We're talking about kHz signals, Fcloc can be MHz or GHz.

\[
\begin{align*}
\text{Ain} &= (V_1 - V_2) \text{Cin} \\
\text{R}_{eq} &\text{ is the same, but now we have both positive and negative integrators.}
\end{align*}
\]

This is useful for biquads and ladder simulators where we need both positive and negative integrators.

The details of the switches are also important:

continued
Caps A, B are connected to $V_i, V_2$ and don't transfer any Q through switches.
Caps C, H are always at 0 volts, with no charge.
Caps D, F charge up to $V_2$ and transfer $Q_2 = V_2(C_0 + C_f)$ to ground each cycle.
Caps C, E are problems. They transfer $Q_1 = V_i(C_0 + C_f)$ to the op-amp each cycle, so they look like extra resistors to $V_i$.
We set $V_i = 0$, and $V_2$ works well as a positive integrator circuit.
What about a negative integrator?

Run the switches with opposite phase.
Think about which direction current flows in each case.

$V_o(s) = \frac{V_i}{sC_1} - \frac{V_2}{sC_f}$

$Z_1 = C_f R Q_1 = \frac{C_f}{C_f + \text{clock}} = \frac{C_f}{C_1}$

We want $Z \gg \text{clock}$ so $C_f \gg C_1, C_2$.
Current Driver

\[ V_{oc} = V_{in}A \]
\[ I_{sc} = \frac{A(V_{in} - I_{oc}R)}{R} = \frac{A V_{in}}{1 + A} \]
\[ Z_{out} = \frac{V_{oc}}{I_{sc}} = R(1 + A) \rightarrow \infty \]

Voltage Follower

\[ V_{oc} = A(V_{in} - V_{oc}) \]
\[ V_{oc}(1 + A) = A V_{in} \]
\[ V_{oc} = \frac{A}{1 + A} V_{in} \]
\[ I_{sc} = \frac{A V_{in}}{R_{oc}} \]
\[ Z_{out} = \frac{V_{oc}}{I_{sc}} = \frac{R_{oc}}{1 + A} \rightarrow 0 \]

Feedback makes either supply more constant (independent of load)
Current source wins: high \( Z_{out} \), Voltage Source wins for low \( Z_{out} \)
Note that stability depends on \( Z_{load} \), e.g. magnetic coil driver

\[ B = \frac{R}{R + sL} = \frac{1}{1 + sL/R} \rightarrow \text{low pass filter} \quad \text{with } \gamma = R/L \]

This pole in transfer function reduces phase margin, could lead to instability.

Compensate by adding a zero

\[ B = \frac{R + sL}{R + sL + kL} \]

\[ = \frac{1 + sLe/R}{1 + s(L + Le)/R} \]

either \( sL \) or \( Le \) works

\[ \text{or } \]

\[ \text{either } R \text{ or } Le \text{ works} \]
Power Supplies

Steady power in residential appliances costs ~ $3B/year
in the USA alone, or 64×10^6 MWh/year
or 18-400MW power stations running full time

Converting to high efficiency power supplies would reduce by factor of 10.
Equivalent to 18M cars worth of CO2

Power supplies convert power from one source to another, e.g. 120VAC to 12VDC
Needs low output resistance so Vout independent of Iout
Also needs Vout independent of Vin

AC distribution: $P = VI$, but loss = $I^2R$, so usually use high $V$
It is easy to change AC voltages with transformers

AC→DC rectification:

Voltage reference:
- Zener diode $V_z$

Zener diode provides a good reference voltage.
However, power is drawn from the source regardless of the load.
Series regulator

![Diagram of series regulator with equations:]

\[ P_{in} = i_{load} \cdot V_{in} \]
\[ P_{out} = i_{load} \cdot V_{out} \]
\[ G = \frac{P_{out}}{P_{in}} = \frac{V_{out}}{V_{in}} \]

Feedback circuit looks like this:

![Diagram of feedback circuit with emitter follower schematic.]

Emitter follower will have time constant due to load capacitance. This may affect phase margin.

Voltage reference would likely be "bandgap reference" which compensates for temperature variations. Uses \( V = 1.25 \) near bandgap of silicon.

![Diagram of voltage reference with equations:]

We generate 5V by dividing \( V_{out} \) by 4 before comparing with \( V_{ref} \).
How do we handle $V_{in} \gg V_{load}$?

Average voltage $V_{avg} = V_{in} \frac{2T}{T}$ can be $\ll V_{in}$

Store energy in a reactance in between pulses

Need a reactive low-pass filter

$\begin{align*}
V_{in} & \quad \text{Fast} \\
\uparrow & \quad \downarrow \\
V_{in} & \quad V_{out}
\end{align*}$

$V_L = L \frac{dI}{dt} = V_{in} - V_{out} > 0$

$V_L = L \frac{dI}{dt} = 0 - V_{out} < 0$

The larger the inductor, the smaller the current ripple

$V_{in}$

$\text{if } V_{out} < V_{ref},$

$\text{the pulse width increases and } V_{out} \text{ starts to rise}$