Exercise 1

A driver circuit should be designed that is based on the stepwise charging technique.

a) Suggest a circuit that charges a capacitive output in two steps ($V_{dd}/2$, V_{dd}).

b) How much energy could be saved using a two step driver compared with a conventional driver that charges the output in one step?

c) How much energy is stored in the output capacitance using a two step driver compared with a conventional driver that charges the output in one step?

Exercise 2

Consider a stepwise charging of a capacitive load. Two power supply voltages (V_{dd1}, V_{dd2}) are used.

a) Determine the dissipated energy. Let $V_{dd1} < V_{dd2}$ and assume that the steps are long in time.

b) Determine the optimal voltage V_{dd1} and the corresponding energy dissipation.

Exercise 3

A large capacitive load C should be charged adiabatically with a power clock $\phi(t)$ connected to a transmission gate according to Figure 1.

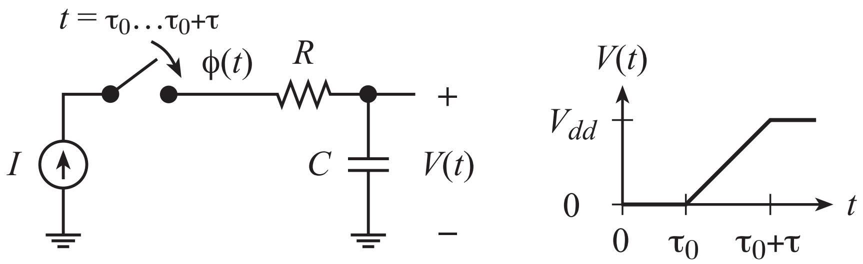


Figure 1. Adiabatic charging of capacitive load.

a) Explain the purpose of using a power clock.

b) Derive an expression for the energy dissipation of the circuit during a charge with the power clock. Assume that the resistance of the transmission gate in its on state is constant R.

c) Determine τ so that the dynamic power dissipation becomes equal to 50% of a conventional static CMOS circuit during charge of the same load.

Exercise 4

In an adiabatic circuit, power clocks are used instead of a constant power supply voltage. In Figure 2, an RC circuit with a power clock is shown. *R* is the equivalent resistance of a T-gate consisting of an NMOS-transistor in parallel with a PMOS-transistor. *T* is the rise and fall time of the complete ramp.

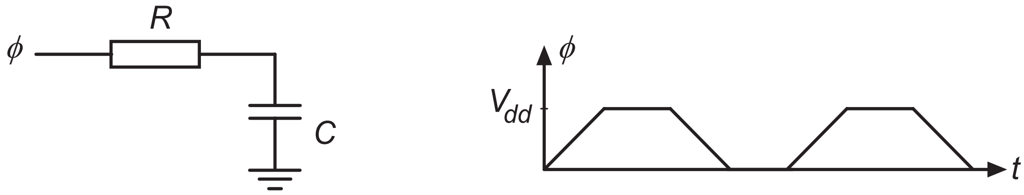


Figure 2. RC circuit powered by a power clock ϕ.

a) The energy dissipated during charging or discharging the capacitance with an ideal ramp as input ϕ can be shown to be

$$E = \left(\frac{RC}{T}\right) C V_{dd}^2 \left(1 - \frac{RC}{T} + \frac{RC}{T} e^{-T/RC}\right) .$$

Determine *T* so that the power dissipation is less than 10% of a conventional static CMOS.

b) Determine the dissipated energy when the voltage over the capacitor is an ideal ramp with the slope of Vdd/T when charging. Determine T so that the power dissipation is less than 10% of a conventional static CMOS.

Exercise 5

An adiabatic amplifier is shown in Figure 3. Explain the operation of the circuit in general, and how the inputs are applied in particular.

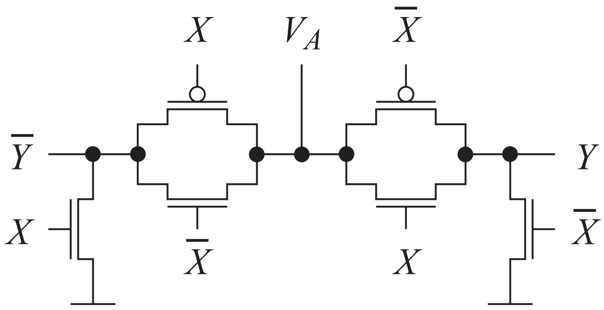


Figure 3. Adiabatic amplifier.

Exercise 6

Design an adiabatic AND/NAND circuit and explain the function of the individual transistors.

Exercise 7

Determine the function of the adiabatic circuit shown in Figure 4, where ϕ is a power clock. Describe how the power clock and the inputs are applied.

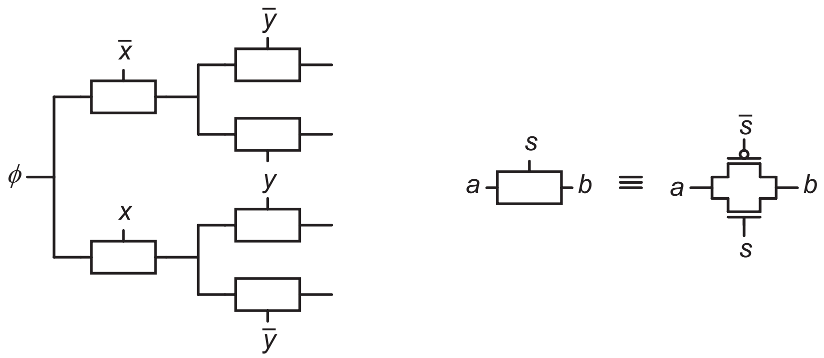


Figure 4. Circuit consisting of six transmission gates.

Exercise 8

Order the energy harvesting devices below from low to high power generation efficiency.

A. RF receiver in proximity to WiFi transmitter
B. Thermoelectric generator attached to human
C. Outdoor solar cell
D. Thermoelectric generator attached to hot machine
E. Solar cell in office

Exercise 9

An outdoor temperature sensor and wireless link consume the power 0.1 mW on average.

a) The energy density of a Lithium-ion battery is 2.2 J/mm^3. How large battery is required to allow for one year of continuous operation if we assume 80% power efficiency?

b) A 0.2 mm thick solar cell produces on average 60 W/m^2 when the sun is shining. In the month with least sun, the sun shines 30 hours. How large solar cell is needed if it charges the battery with 70% power efficiency?

c) How large battery is needed if the solar cell in b) is used?

Exercise 10

A temperature sensor and wireless link consume on average the power 0.15 mW. How large does the energy harvester need to be to provide enough energy for continuous operation if we are using the technologies below and the power efficiency in charging the battery is 50%?

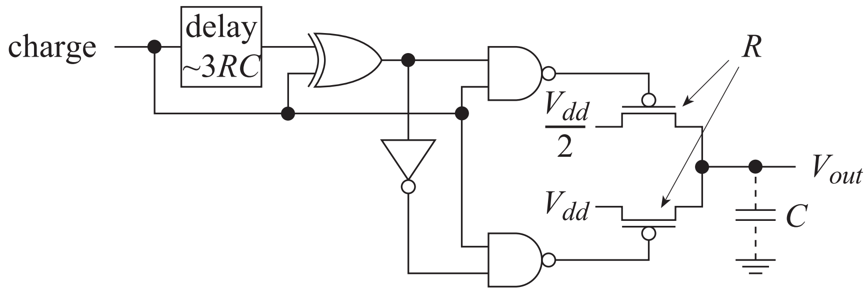
a) A 0.2 mm thick solar cell that produces 100 W/m^2 when the sun is shining. The sun shines on average 1765 hours per year at an outdoor location of employment.

b) A piezoelectric generator that picks up 200 W/m^3 from a vibrating engine. The engine is on 7 hours per work day.

c) A 0.8 mm thick thermoelectric generator that produces 0.5 W/m^2 @ $\Delta T = 5°C$. The generator is mounted on a heated pipe yielding $\Delta T = 8°C$ on average. Assume that the power production scales proportional to the temperature difference.

Solution 1

a) Two step charging circuit:



V_{out} is charged from 0 to ~V_{dd} in time ~6RC

b) Assuming the power supply voltage is V_{dd}, the conventional driver consumes the energy

$$E_{conv} = \frac{CV_{dd}^2}{2}$$

and the two step driver

$$E_{twos} = E_{twos}\Big|_{t=0..3RC} + E_{twos}\Big|_{t=3RC..6RC} = \frac{C\left(V_{dd}/2\right)^2}{2} + \frac{C\left(V_{dd}/2\right)^2}{2} = \frac{CV_{dd}^2}{4}$$

Hence the savings are

$$E_{save} = E_{conv} - E_{twos} = \frac{CV_{dd}^2}{2} - \frac{CV_{dd}^2}{4} = \frac{CV_{dd}^2}{4}$$

c) Both solutions store the energy $CV_{dd}^2/2$ in the capacitor, hence the energy is the same for same power supply voltage.

Solution 2

a) $E_{diss} = C\left(\frac{V_{dd2}^2}{2} + V_{dd1}^2 - V_{dd2}V_{dd1}\right)$

b) $E_{diss} = C\frac{V_{dd2}^2}{4}$ for $V_{dd1} = \frac{V_{dd2}}{2}$

Solution 3

a) The power clock should pulse the charge to the load and then recover the charge back to the power generator with small losses when the charge is no longer needed.

b) To accomplish $V(t)$ with a constant R, the current used for charge and discharge must be constant I. This yields the energy dissipation

$$E_a = P\tau = I^2R\tau = \left(\frac{CV_{dd}}{\tau}\right)^2 R\tau = \frac{RC}{\tau}CV_{dd}^2$$

c) The dynamic energy dissipation of a conventional circuit is

$$E_s = \frac{CV_{dd}^2}{2} \Rightarrow E_a = 2\frac{RC}{\tau}E_s$$

To achieve $E_a = 0.5E_s$, $2\frac{RC}{\tau} = 0.5 \Rightarrow \tau = 4RC$

Solution 4

a) Solve the equation

$$\frac{RC}{T}CV_{dd}^2\left(1-\frac{RC}{T}+\frac{RC}{T}e^{-T/RC}\right) = 0.1\frac{CV_{dd}^2}{2}$$

by e.g. setting $x = T/RC$

$$\frac{1}{x}\left(1-\frac{1}{x}+\frac{1}{x}e^{-x}\right) = \frac{1}{20} \Leftrightarrow x = 20\left(1-\frac{1}{x}+\frac{1}{x}e^{-x}\right)$$

end solving the iteration equation

$$x_{n+1} = 20\left(1-\frac{1}{x_n}+\frac{1}{x_n}e^{-x_n}\right)$$

Starting with $x_0 = 1$ yields $x \approx x_4 \approx x_5 \approx 18.94$

Hence $T \approx 18.9\ RC$

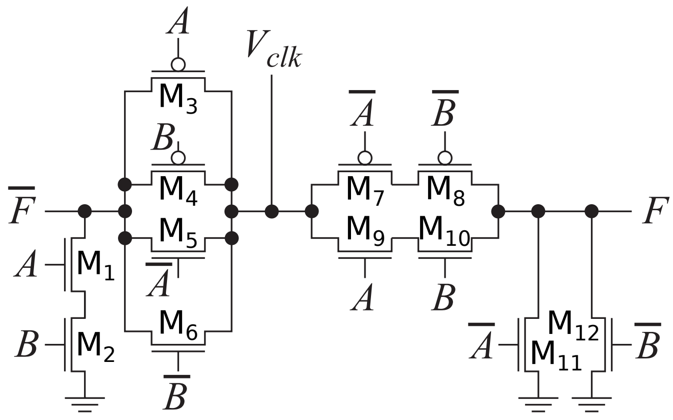
b) $E_{diss} = \frac{RC}{T}CV_{dd}^2$, $T = 20RC$

Solution 5

First, the input is set to a valid value. Next, V_A rises slowly from 0 to V_{dd}. One of the outputs will then be charged adiabatically through one of the transmission gates. The output can now be used. Finally, V_A falls slowly back to 0, and the charges at the output flows back into the power supply.

Solution 6

A two-input adiabatic AND/NAND circuit realizing $F = AB$ is shown in the figure below.



Using the labeling in the figure, the function is as follows. M_5 and M_6 are used for charging and recovering charges of the output when V_{clk} is at a low voltage. M_3 and M_4 are used correspondingly when V_{clk} is at a high voltage. M_1 and M_2 clamps the output to 0 when is evaluated to 0 instead of leaving it floating. M_9 and M_{10} are used for charging and recovering charges of the output F' when is at a low voltage. M_7 and M_8 are used correspondingly when is at a high voltage. M_{11} and M_{12} clamps the output to 0 when F should remain 0.

Solution 7

An address or column decoder. Note that all the outputs always are low after the discharging phase and that only one output is charged during the charging phase.

Solution 8

A. RF receiver in proximity to WiFi transmitter ~ 1 μW/cm2
B. Thermoelectric generator attached to human ~ 50 μW/cm2
E. Solar cell in office ~ 100 μW/cm2
D. Thermoelectric generator attached to hot machine ~ 10 mW/cm2
C. Outdoor solar cell ~ 10 mW/cm2

Solution 9

Data: energy density D = 2.2 J/mm^3, average power needed P_{sensor} = 0.1 mW, operation time $t_{use} \approx 365 \cdot 24 \cdot 60 \cdot 60$ s = 31.5 Ms.

a) Battery volume with efficiency $\eta_b = 0.8$

$$V_{battery} = \frac{P_{sensor} t_{use}}{\eta_b D} \approx 1.8 \text{ cm}^3$$

b) Charge efficiency is ηs = 0.7
Average charge power needed from solar cell is $P_{charge} = P_{sensor}/(\eta_b \eta_s) \approx 179\ \mu W$

Number of hours in a month is $N \approx 24 \cdot 31$ h = 744 h

Average power per area supplied in worst-case month $P_{area} = 60 \cdot 30/744\ W/m^2$

Solar cell area needed to charge battery

$$A = \frac{P_{charge}}{P_{area}} \approx \frac{1.79 \cdot 10^{-4} \cdot 744}{60 \cdot 30}\ \text{m}^2 \approx 7.4 \cdot 10^{-5}\ \text{m}^2 = 0.74\ \text{cm}^2$$

A thickness of 0.2 mm yields a solar cell volume of about 15 mm^3

c) Relying on an average distribution of sun, the battery needs to last 1/12th of a year. Hence the volume is $V_{both} = V_{battery}/12 \approx 150\ \text{mm}^3$. (A pessimistic distribution of sun in beginning and end of subsequent two months would require almost double that size)

Solution 10

Average charge power needed: $P_{charge} = 0.15\ \text{mW}/50\% = 0.30\ \text{mW}$

a) Solar cell volume

$$V_{\text{solar}} = A_{\text{solar}} d_{\text{solar}} = \frac{P_{\text{solar}}}{\text{PPA}_{\text{solar}}} d_{\text{solar}} = \frac{P_{\text{charge}} \frac{h_{\text{year}}}{h_{\text{sun}}}}{\text{PPA}_{\text{solar}}} d_{\text{solar}} = \frac{P_{\text{charge}} h_{\text{year}} d_{\text{solar}}}{\text{PPA}_{\text{solar}} h_{\text{sun}}} =$$

$$= \frac{0.30 \cdot 10^{-3} \cdot 365 \cdot 24 \cdot 0.2 \cdot 10^{-3}}{100 \cdot 1765}\ \text{m}^3 \approx 3.0\ \text{mm}^3$$

b) Piezoelectric generator volume

$$V_{\text{piezo}} = \frac{P_{\text{piezo}}}{\text{PPV}_{\text{piezo}}} = \frac{P_{\text{charge}} \frac{h_{\text{year}}}{h_{\text{work}}}}{\text{PPV}_{\text{piezo}}} = \frac{P_{\text{charge}} h_{\text{year}}}{\text{PPV}_{\text{piezo}} h_{\text{work}}} =$$

$$\approx \frac{0.30 \cdot 10^{-3} \cdot 365 \cdot 24}{200 \cdot 7 \cdot 5 \cdot 52}\ \text{m}^3 \approx 7.2\ \text{cm}^3$$

c) Thermoelectric generator volume

$$V_{\text{thermo}} = A_{\text{thermo}} d_{\text{thermo}} = \frac{P_{\text{charge}} d_{\text{thermo}}}{\text{PPDT}_{\text{thermo}} \frac{\Delta T}{\Delta T_{\text{thermo}}}} = \frac{0.30 \cdot 10^{-3} \cdot 0.8 \cdot 10^{-3}}{0.5 \cdot \frac{8}{5}}\ \text{m}^3 = 300\ \text{mm}^3$$