Università degli Studi di Padova
Laurea Magistrale in Ingegneria Elettronica

Analysis and implementation of a cold start oscillator for ultra low voltage energy harvesting applications

LAUREANDO: MARCO PIOVESAN
RELATORE: CH.MO PROF. LUCA CORRADINI

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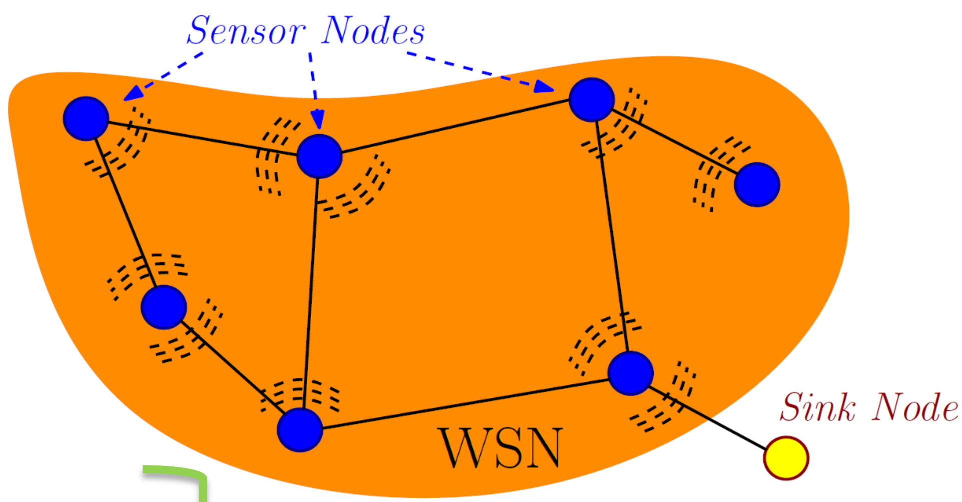
Motivating Example: Wireless Sensor Networks

Function of a WSN:

- Sense and sample: temperature, pressure, humidity, etc…
- Route sensed information to a central unit or *sink node.*



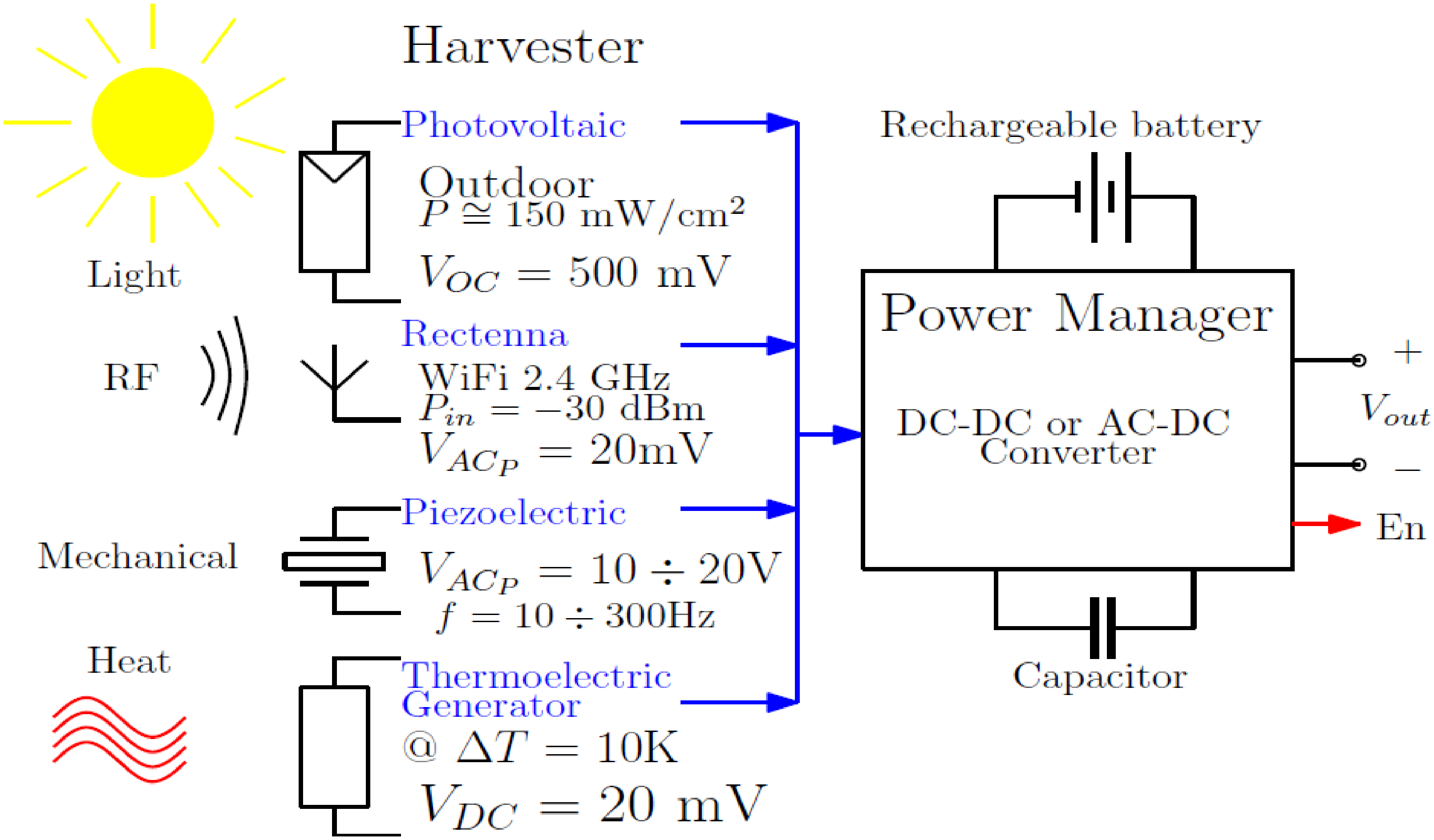
Large-scale WSN:
tens to hundreds of nodes

Practical deployment of large-scale WSN's implies:

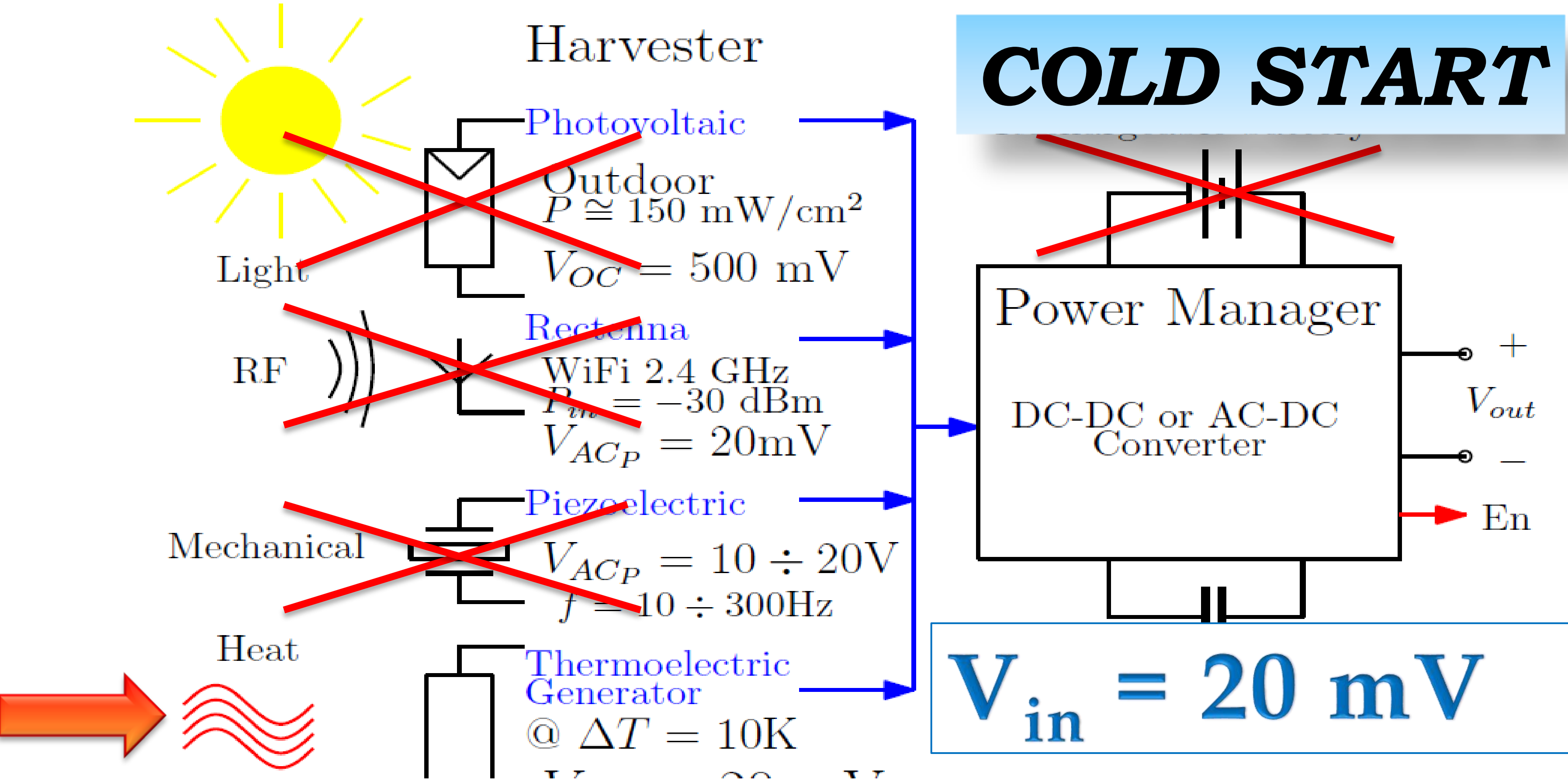
- Zero-maintenance nodes ("Fit and forget"philosophy)
- Prolonged sensor lifetime (e.g. > 2 years)
- Low $/Wh

→ **Energy Harvesting**

Energy Harvesting System

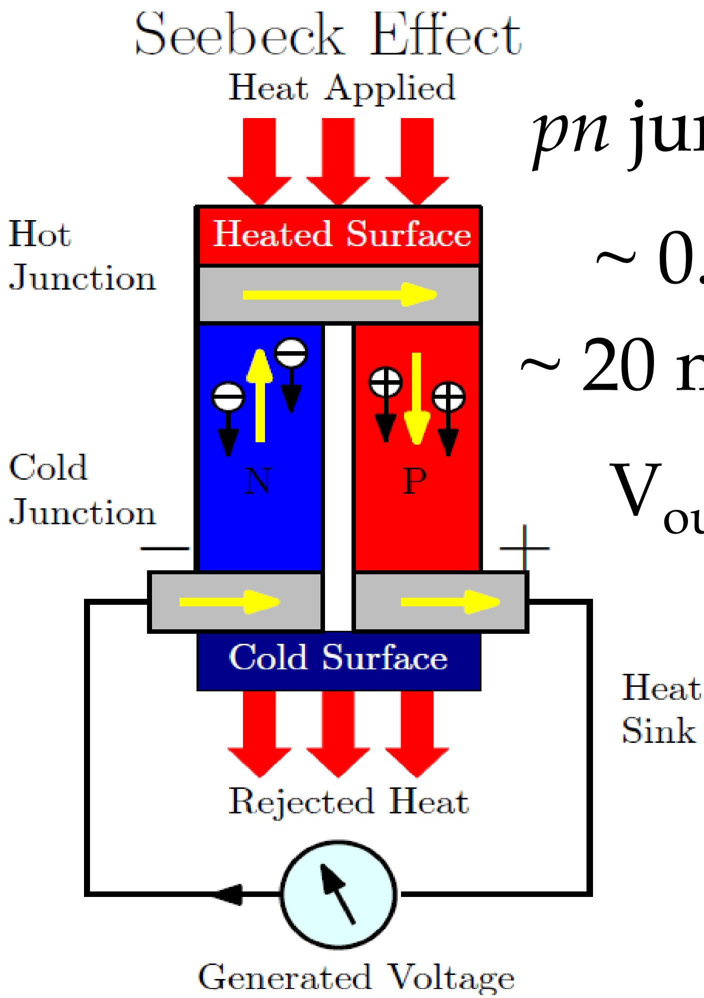


Energy Harvesting System



Thesis goal: to develop a cold start circuit for the thermoelectric generator.

Thermoelectric Generation

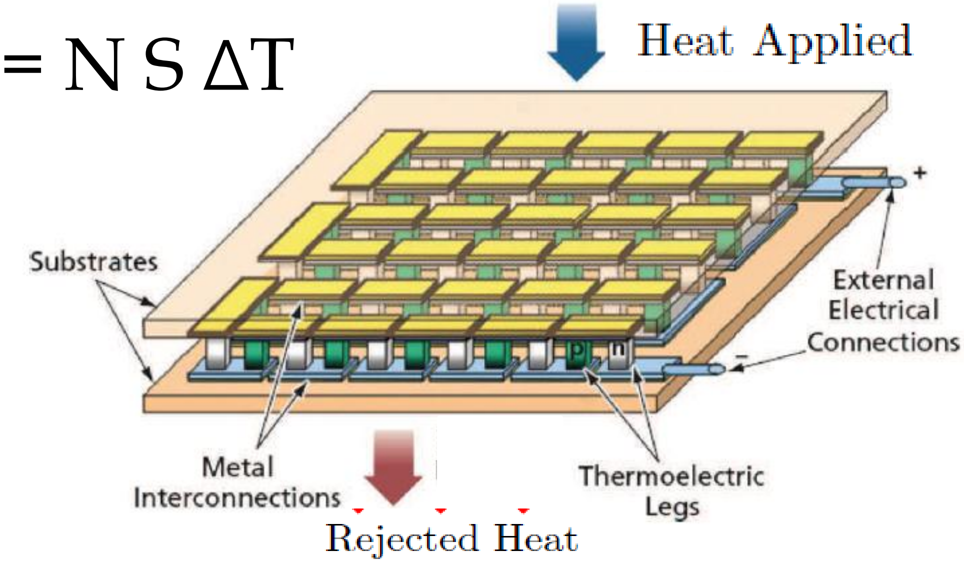


pn junction – Bi_2Te_3

~ 0.2 mV/K per cell

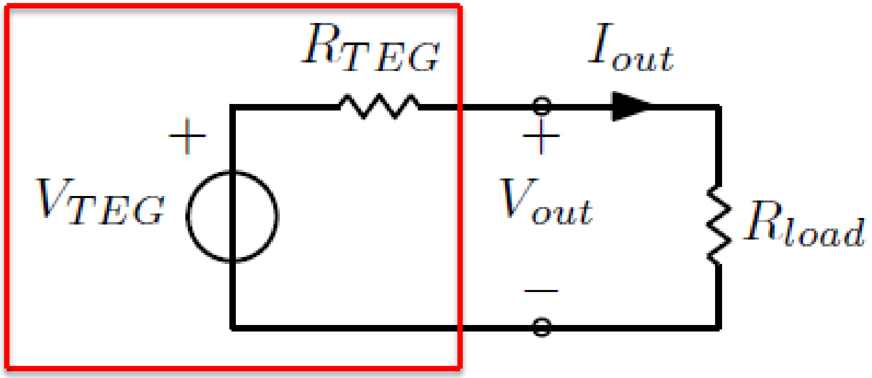
~ 20 mV with 10 cells at ΔT = 10 K

$V_{out} = N\,S\,\Delta T$



Thermoelectric Generation

Thévenin equivalent circuit:

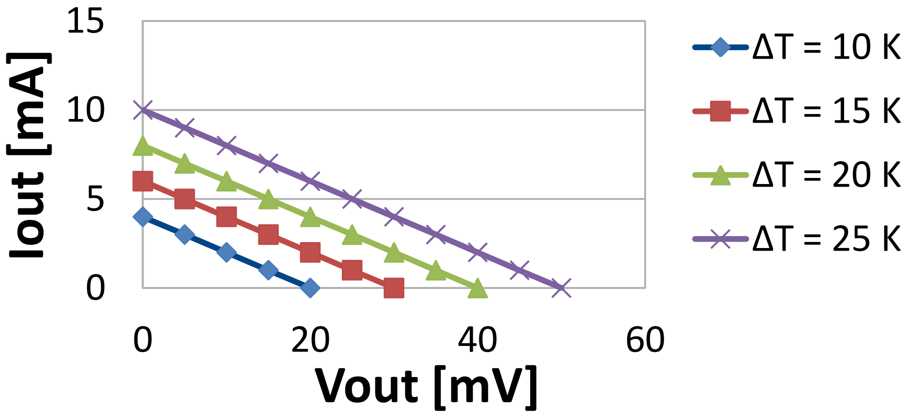


Typ.

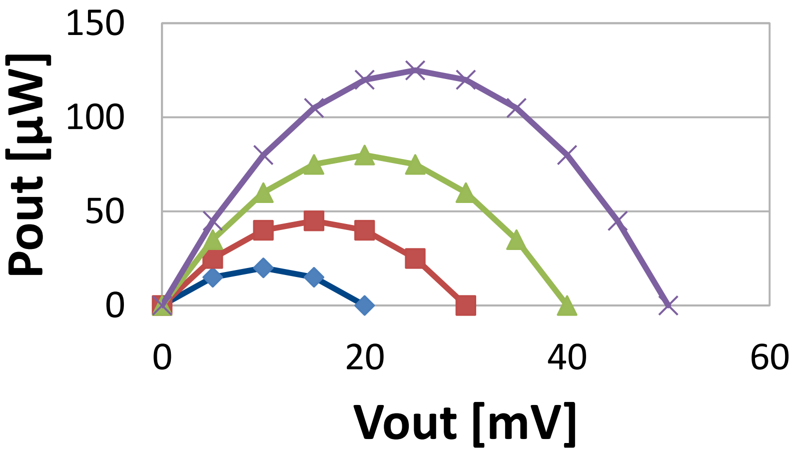
R_{TEG} = 2.5 Ω

V_{TEG} = ~2 mV/K

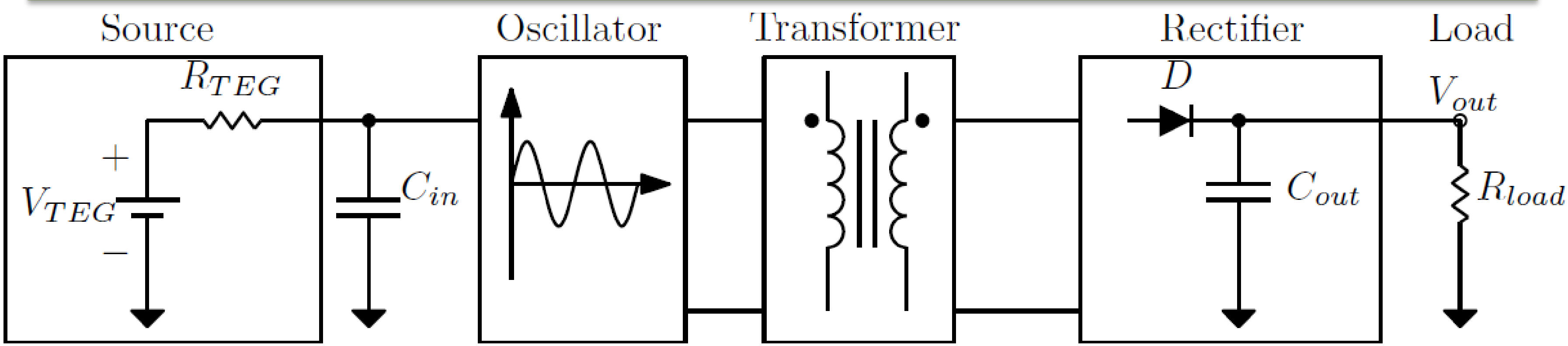
Iout vs. Vout @ Delta T



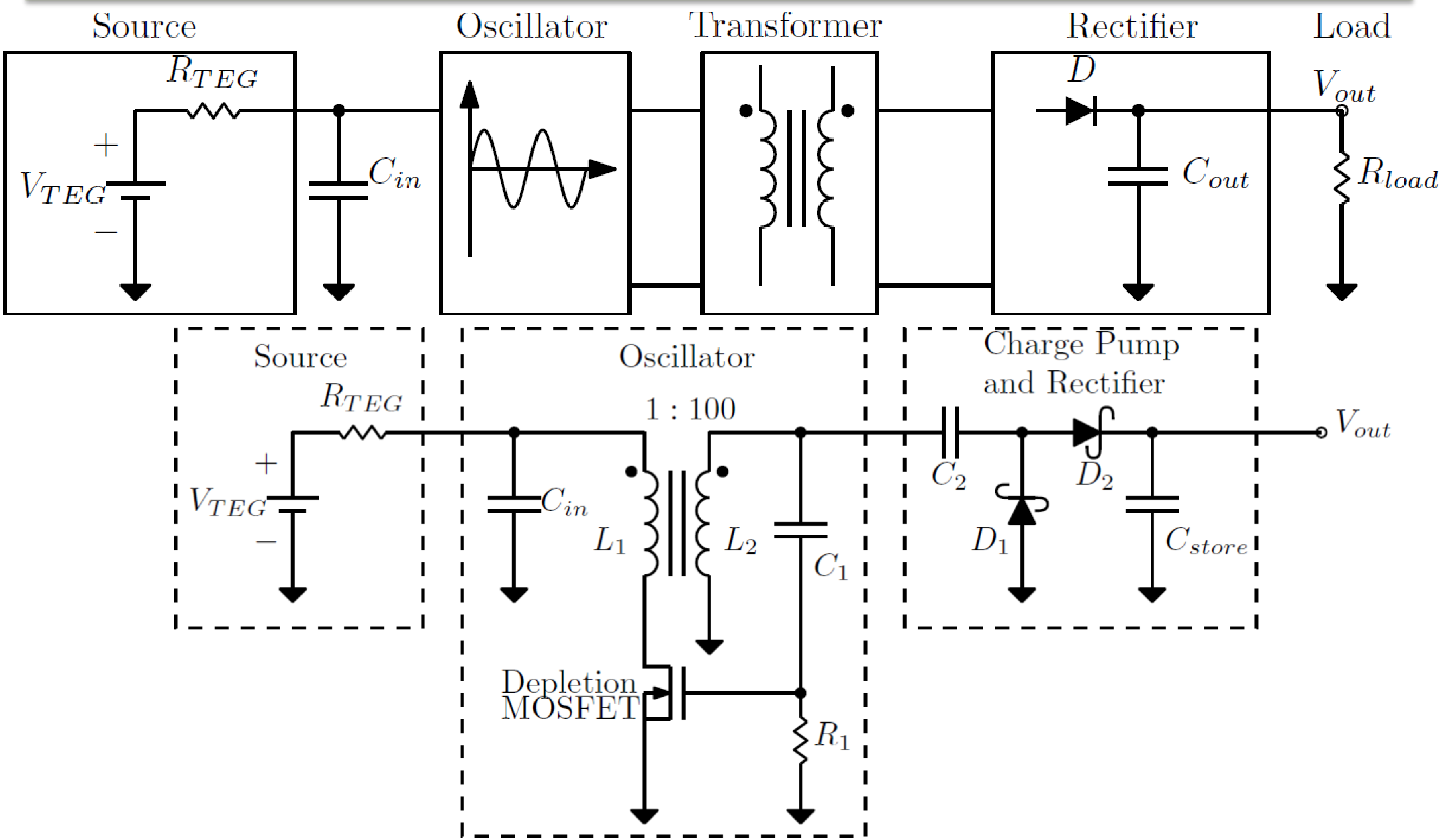
Pout vs. Vout @ ΔT



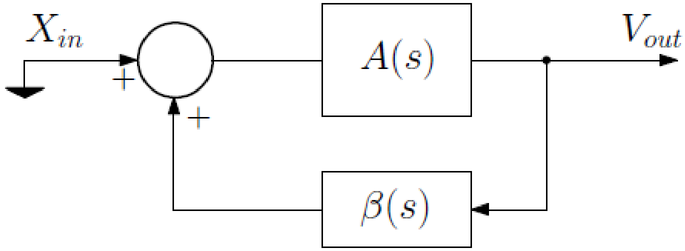
Cold Start Oscillator for Ultra Low-Voltage Sources



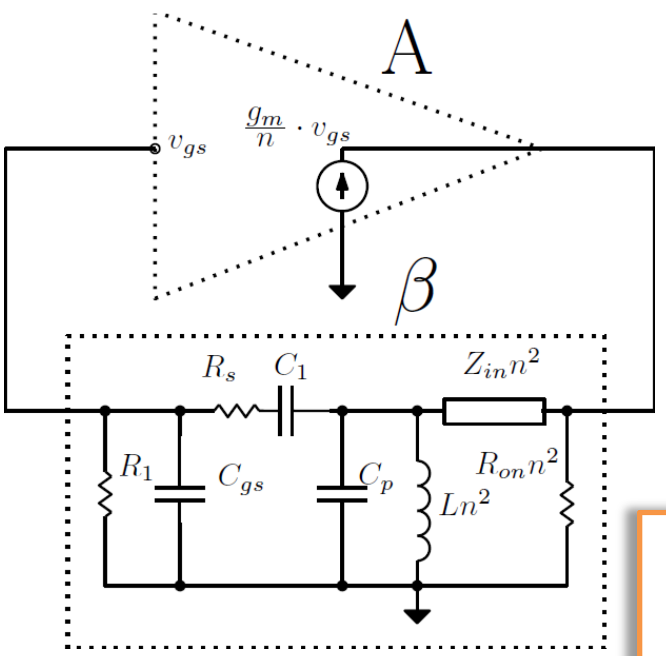
Cold Start Oscillator for Ultra Low-Voltage Sources



Oscillator Analysis and Start-Up Condition



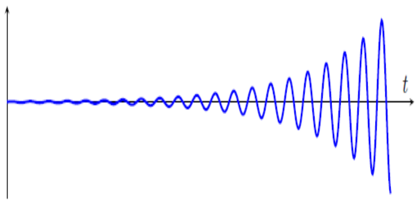
$$1 - A(s)\beta(s) = 0 \quad \Rightarrow \quad 1 - T(s) = 0$$



Start-up condition

$$|T(j\omega_0)| > 1$$

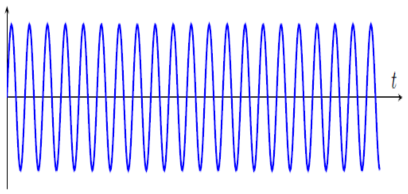
$$\angle T(j\omega_0) = 0^\circ$$



Barkhausen criterion

$$|T(j\omega_0)| = 1$$

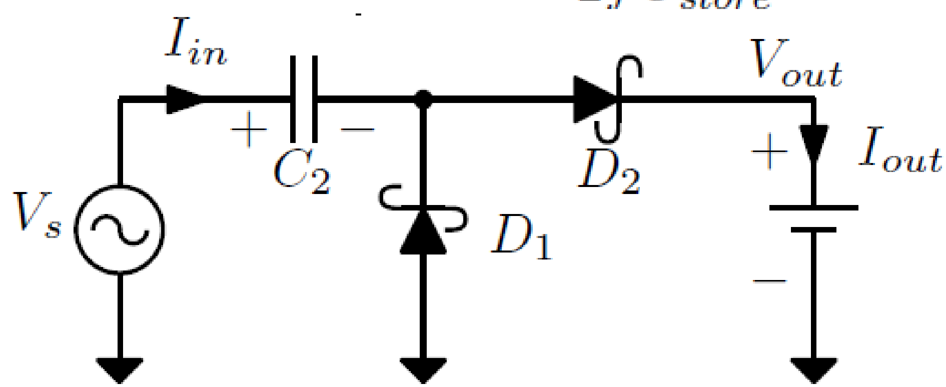
$$\angle T(j\omega_0) = 0^\circ$$



$$T(j\omega_0) = \frac{g_m}{n} \frac{R_{on} \cdot n^2 \cdot (R_1||R_{in})}{R_{on} \cdot n^2 + [(R_1||R_{in}) + (R_s + R_p \cdot n^2)]}$$

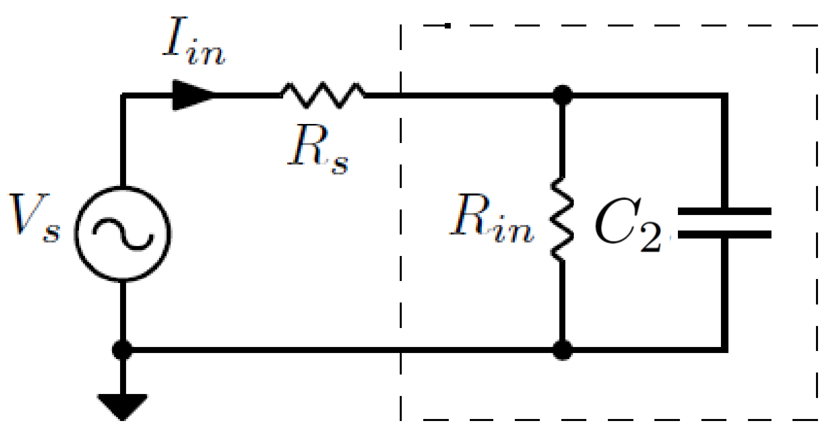
Analysis of the Rectifying Cell

$$V_{out} = 2V_{M_{in}} - \frac{I}{2fC_{store}}$$

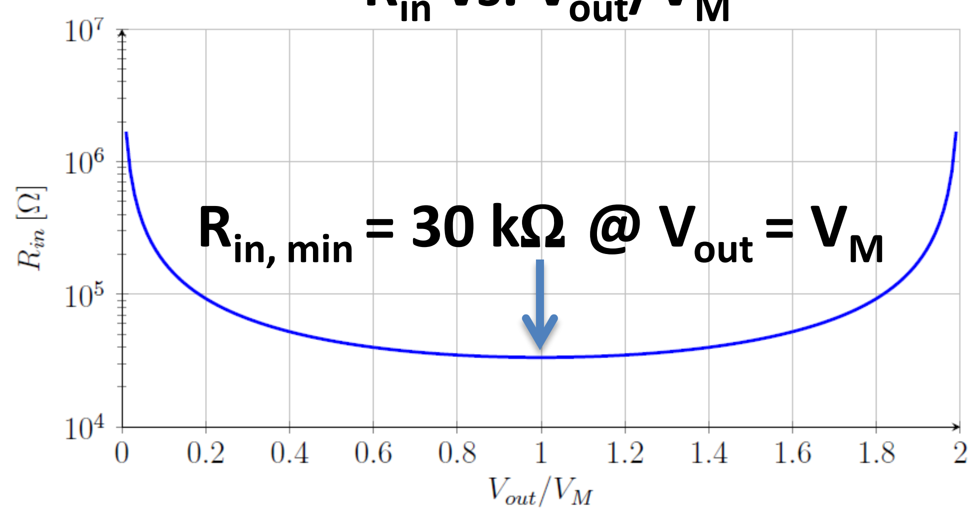


$$R_{in} = \frac{1}{2 \cdot C_2 \cdot f \cdot \sin^2(\Delta\theta)}$$

$$\Delta\theta = \frac{\pi}{2} - \arcsin\left(\frac{V_{out}}{V_M} - 1\right)$$

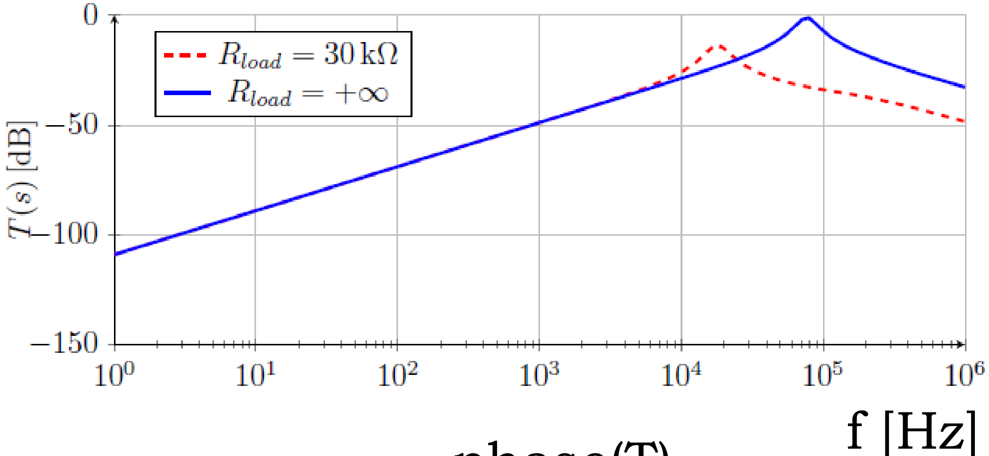


R_{in} vs. V_{out}/V_M

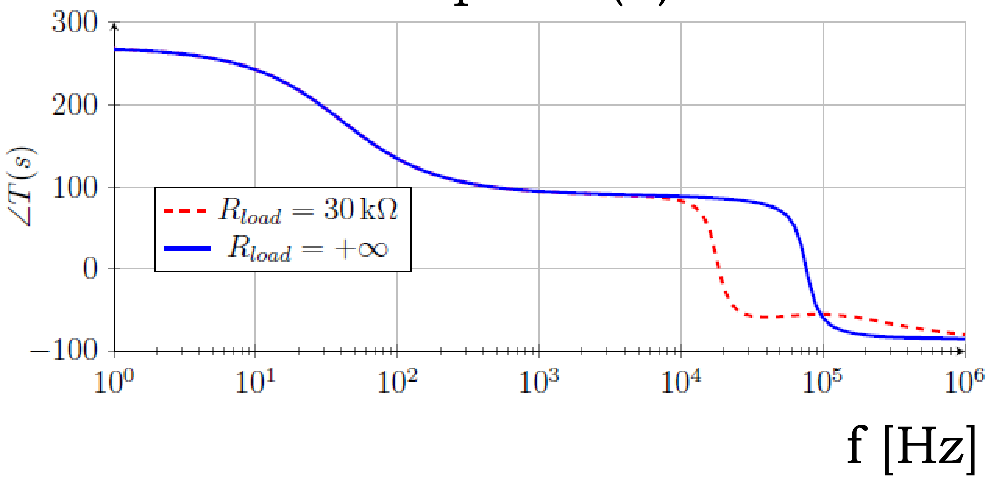


Loop Gain and Design Curves

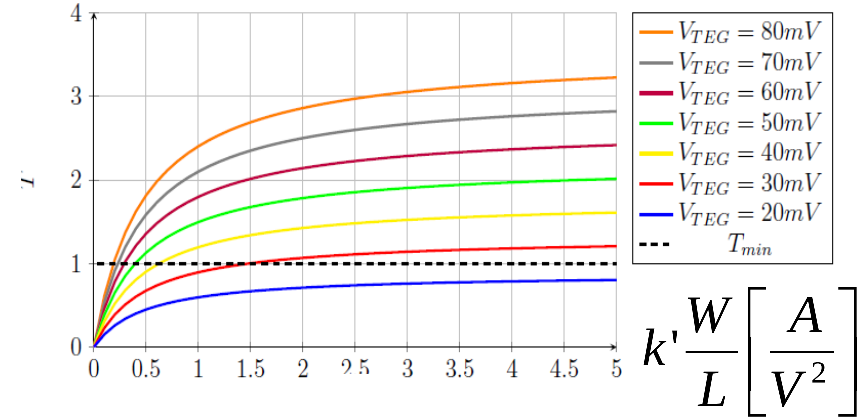
|T|$_{dB}$



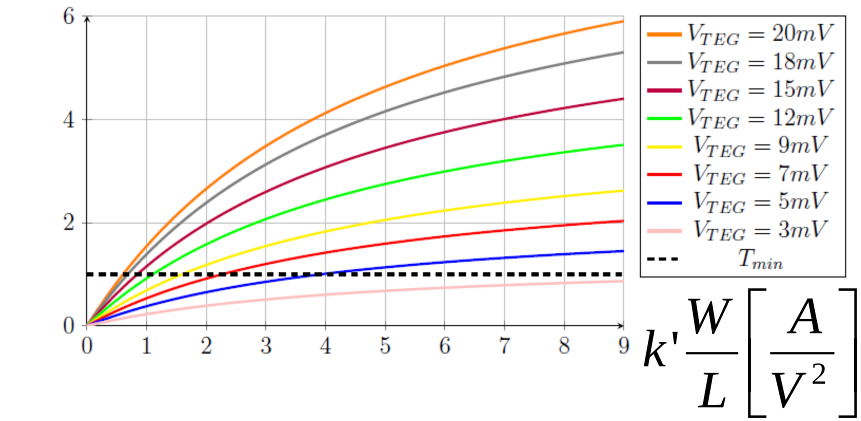
phase(T)



|T| vs. k'W/L **V_{th} = -1 V**

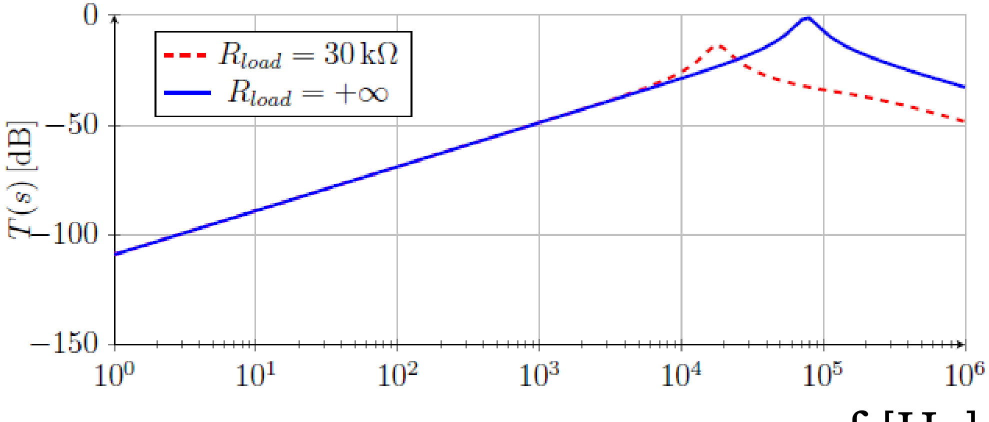


|T| vs. k'W/L **V_{th} = -0.1 V**

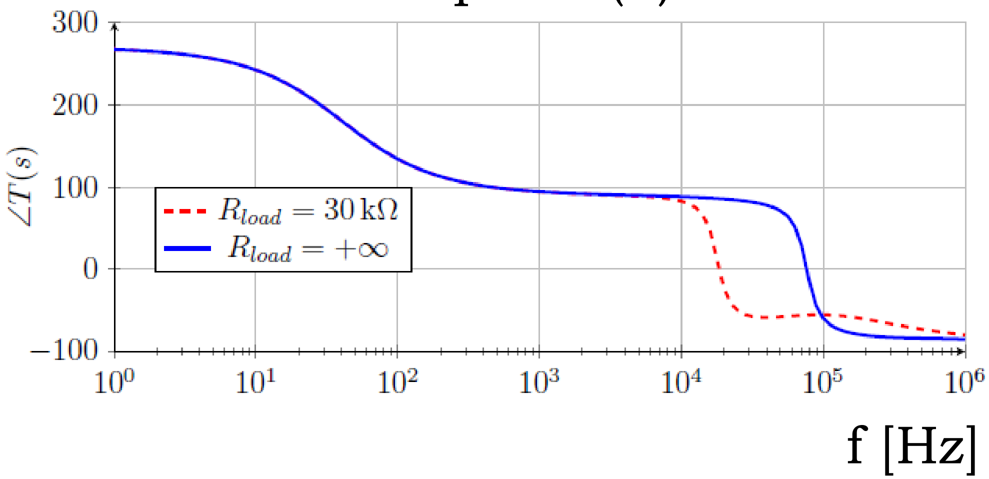


Loop Gain and Design Curves

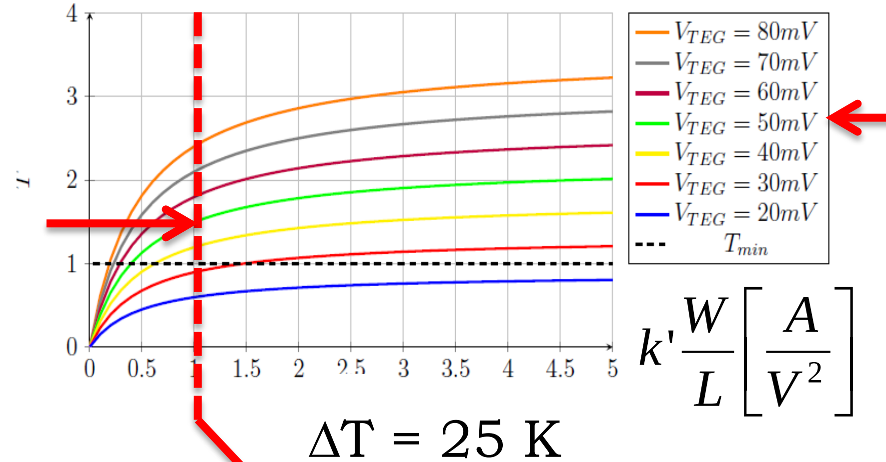
|T|dB

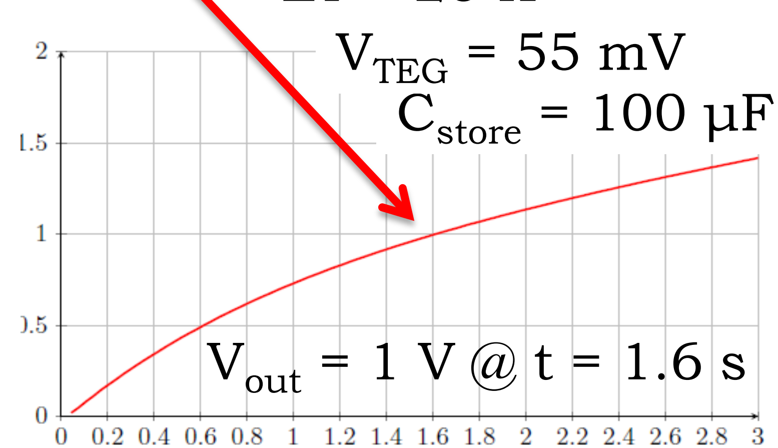


phase(T)



|T| = 1.5 @ k'W/L = 1 A/V²

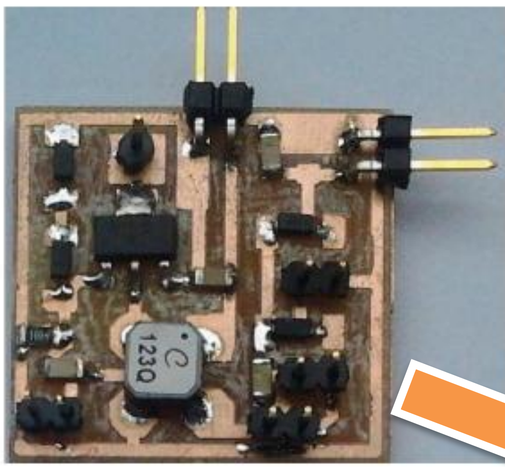


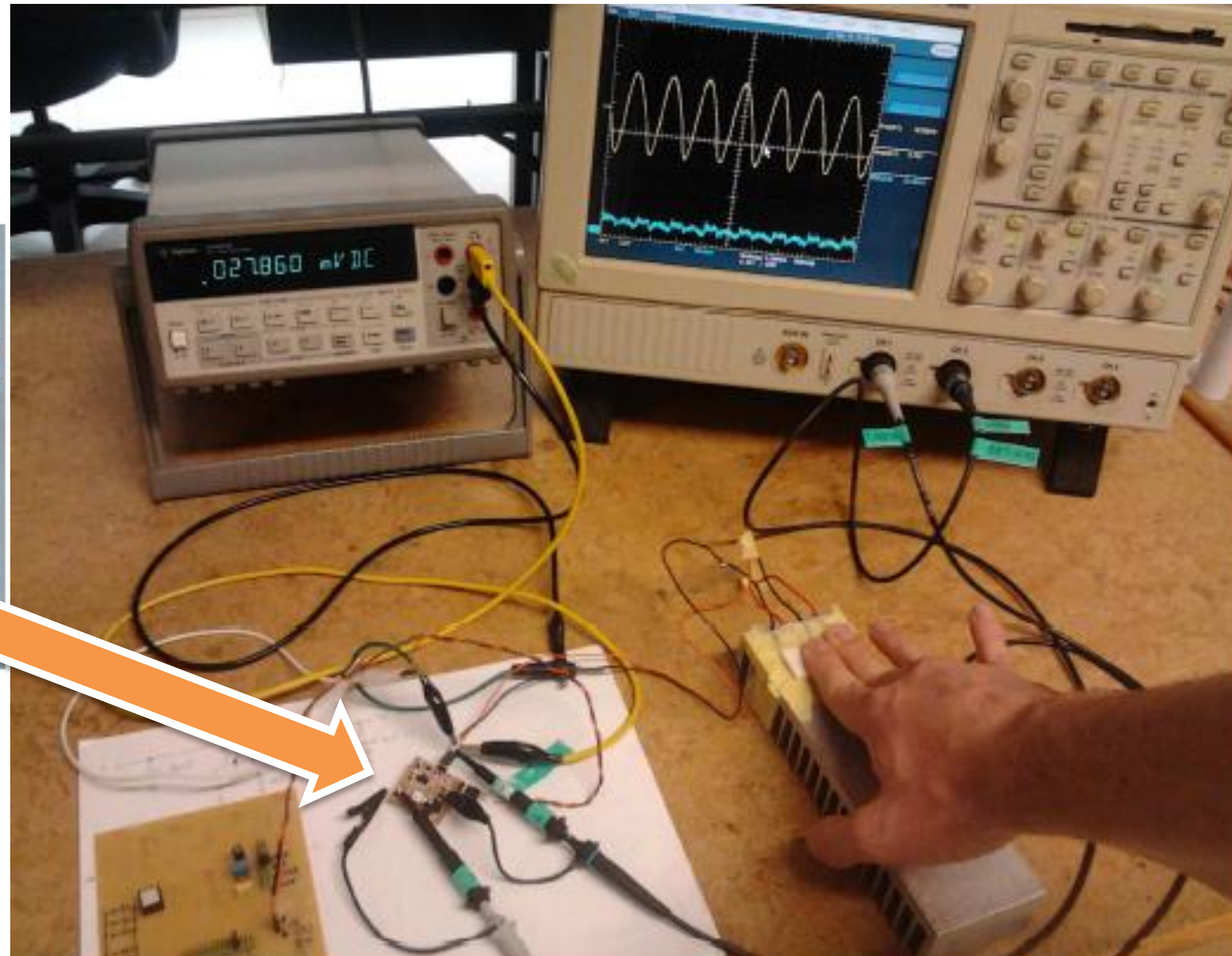


Prototype Supplied with the Thermoelectric Generator

$\Delta T = 10\ K$

$V_{START\text{-}UP} = 35\ mV$





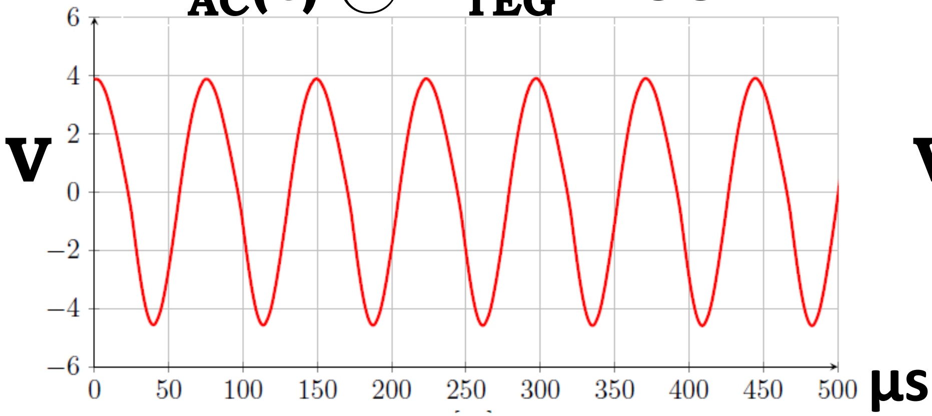
$V_{OUT} = 2.4\ V$

$P_{OUT} = 60\ \mu W$

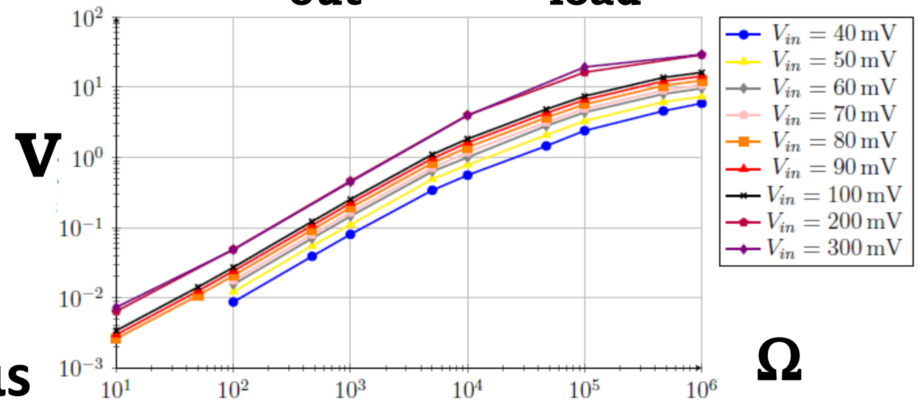
$\eta = 25\%$

Test and Measures

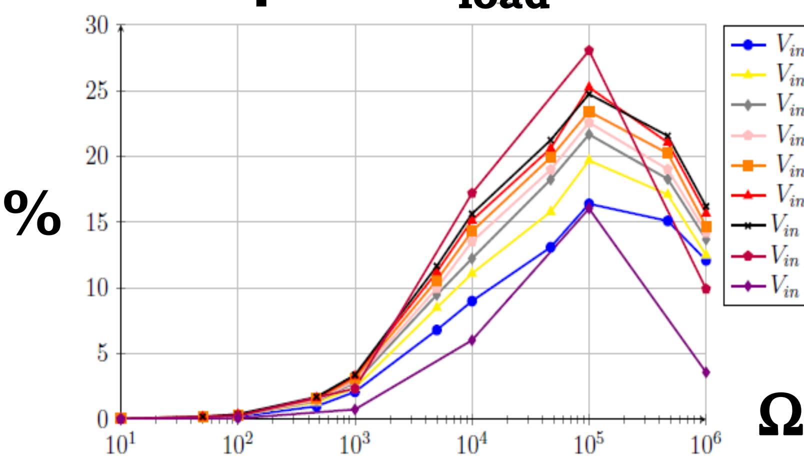
$V_{AC}(t)$ @ V_{TEG} = 55 mV



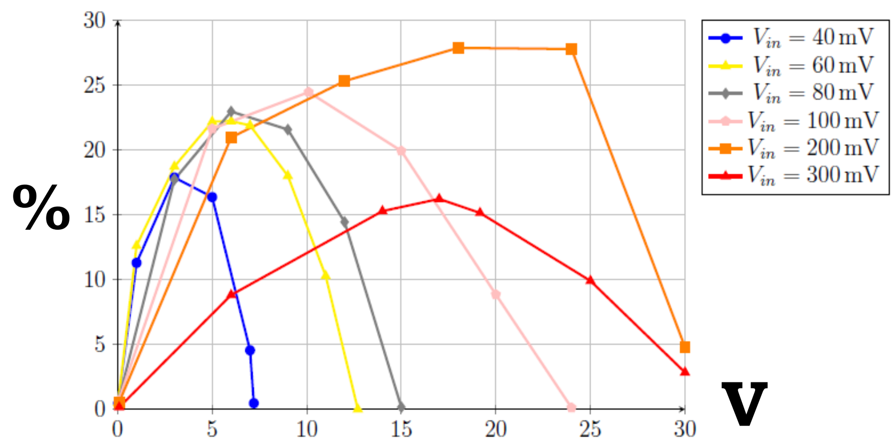
V_{out} vs. R_{load}



η vs. R_{load}



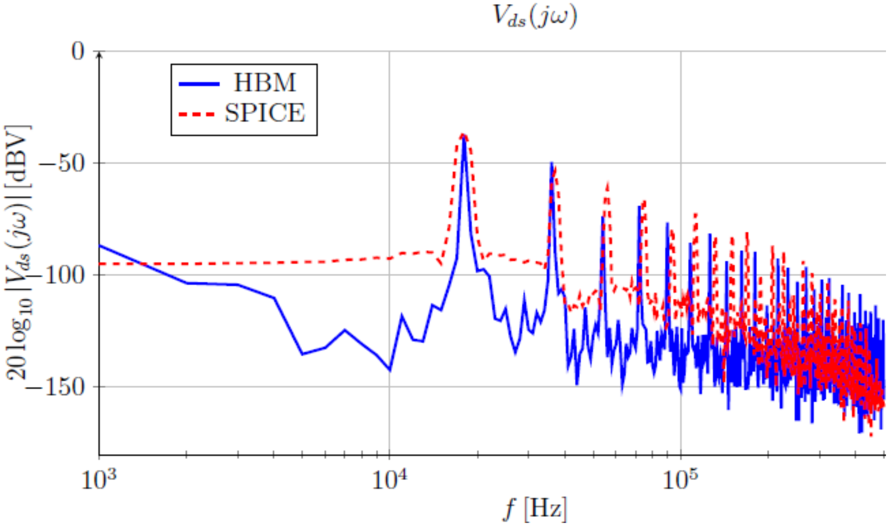
η vs. V_{out}

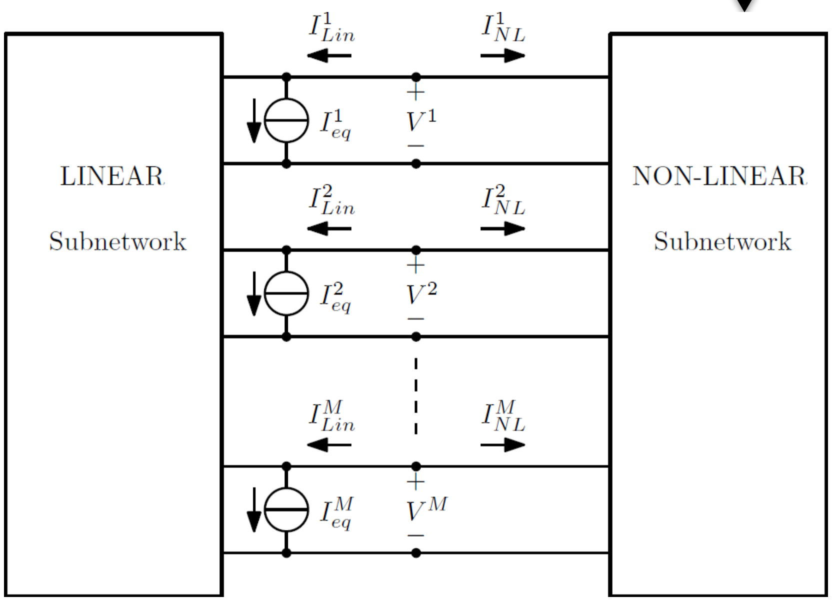


Additional Contribution: Non-Linear Circuit Simulation

Harmonic Balance Method ➡ Piecewise Harmonic Balance

- Preliminary study of the method;
- Application of the Piecewise Harmonic Balance on the oscillator circuit;
- Matlab implementation of the algorithm;
- Simulation and comparison with SPICE.





$$\mathbf{F(V) = I_{Lin} + I_{NL} = 0}$$

Summary

- This thesis focused on a cold-start oscillator for ultra low-voltage sources employed in energy harvesting applications;
- The oscillator and voltage multiplier stages were studied both theoretically and on simulation;
- A prototype of the circuit was developed and tested,

  the measured start-up voltage is $V_{start\text{-}up} = 35\ mV$;
- An additional contribution of non-linear circuits simulation: preliminary implementation of the Harmonic Balance Method.