Voltage Sources and Clock Generators

Avionics and Spacionics

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Introduction

General Specifications

- **Input**: 90 to 135 Vac, 47 – 63 Hz
- **Inrush current**: 30 A cold start; 60 A warm start
- **Efficiency**: > 80% at nominal loading
- **Output Voltages/Regulation/Ripple**:

Channel	Vout	Output type	Regulation	Max Ripple	Current	Surge
1	2.6 V	Buck reg.	+/-1%	40 mVp/p	3 A	4 A
2	3.3 V	Buck reg.	+/-1%	40 mVp/p	4 A	5 A
3	5 V	Main output	+/-2%	50 mVp/p	3 A	4 A
4	6.2 V	Quasi-reg.	+/-6%	50 mVp/p	1.5 A	2 A
5	9 V	3-T reg.	+/-1%	30 mVp/p	100 mA	200 mA
6	12 V	Main output	+/-2%	50 mVp/p	1 A	3 A
7	30 V	Quasi-reg.	+/-8%	100 mVp/p	20 mA	40 mA
8	-5 V	3-T reg.	+/-1%	30 mVp/p	30 mA	60 mA

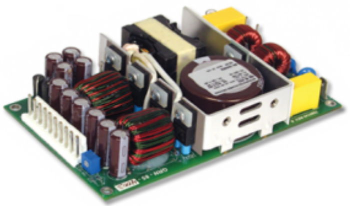
Example of specs for a power supply, "On Semiconductor Multi-Output Flyback Off-Line Power Supply"

- Today's spacionics and avionics electronic designs require an increasing number of power rails and supply solutions. These exhibit:
  - Different voltage levels, different output currents (from a few mA to 100's of A), different stability and accuracy levels, ...
  - Such diversity implies that different types o circuits/components have to be used
- Spacionics and avionics electronic circuits often need oscillators, e.g. for timing purposes or to supply digital components
- This module introduces some of the basic requirements, circuits and components used for generating voltage sources and oscillator circuits

Introduction

Topics:

- Voltage sources: principles and circuits
    - linear DC-DC converters
    - switching DC-DC converters
- Precision voltage sources
- Oscillator circuits
    - RC oscillators
    - Crystal oscillators



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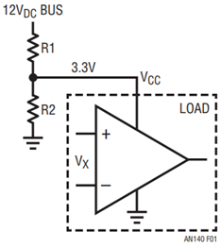
A trivial solution ...

Problem: get 3.3V to fed an OpAmp from a 12 V battery.

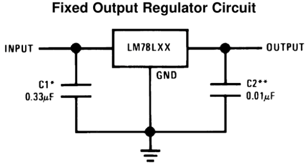


Source: https://www.analog.com/en/resources/app-notes/an-140.html

Trivial solution ... Does it work? Why?

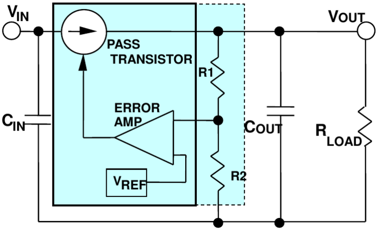
Linear regulators fundamentals

- Linear regulators use a voltage-controlled current source to force a fixed voltage at the regulator output terminal.
    - Control circuitry continuously senses the output voltage and adjusts the current source to maintain the output voltage at the desired value.
- The output voltage is thus controlled using a feedback loop, which requires some type of compensation to assure loop stability. Most linear regulators have built-in compensation, and are completely stable without external components ...
- But some regulators (typically Low-Dropout, but not only), require some external capacitance connected from the output lead to ground to assure regulator stability. Some others also require a minimum current (load) to operate properly. **Respect strictly the indications of the datasheets**



From Texas Instruments LM78L datasheet

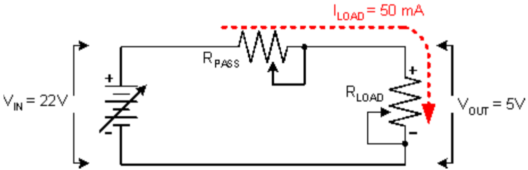
Linear regulators fundamentals



- Voltage feedback samples the output
- R1 and R2 may be internal or external
- Feedback loop controls the current supplied to C_{OUT} and thus the output load
- The pass transistor (bipolar or FET) operates in its linear region and thus works as a variable resistor in series with the output load

Linear regulators fundamentals

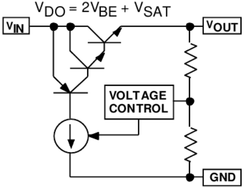
Equivalent model (simplified)



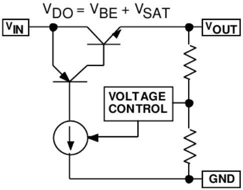
- V_{IN} and R_{LOAD} vary over time
- R_{PASS} is adjusted dynamically so that V_{OUT} is kept constant

Linear regulators fundamentals

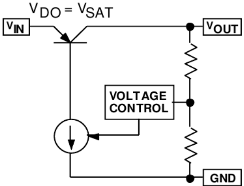
Linear regulator topologies



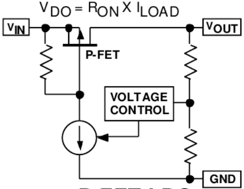
NPN DARLINGTON



NPN QUASI-LDO



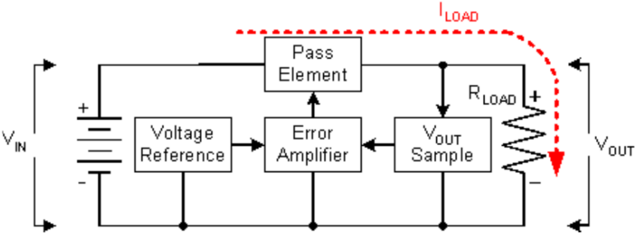
PNP LDO



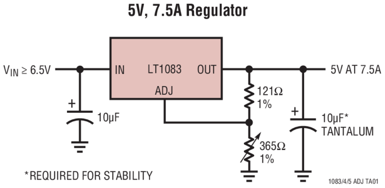
P-FET LDO

Linear regulators fundamentals

A more complete model ...



3-Terminal Adjustable linear regulators



Source: LT1083 series datasheet

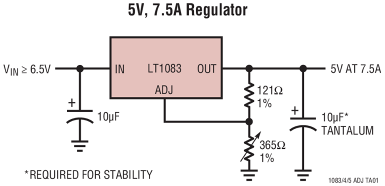
- Linear regulators typically offer several types of protection (overloads, short circuit, ...)
- Some of them have a fixed output voltage, while other are adjustable via external components
- E.g. the LT1083 Series adjustable regulators provide 3-A to 7.5A.

$$V_{OUT} = V_{REF}(1 + \frac{R_2}{R_1}) + I_{ADJ} \cdot R_2$$

As I_{ADJ} is $50\mu A$ the second parcel can be neglected

$V_{REF} = 1.250V$

3-Terminal Adjustable linear regulators



Source: LT1083 series datasheet

- Assume that potentiometer is $1k\Omega$. What is the voltage range you can get? (Hint: use the datasheet)

- Note the requirement for a tantalum capacitor - impacts on stability
- R1 and R2 often are precision resistors with low thermal drift to improve accuracy

Linear regulators evaluation

- Linear regulators have been widely used by industry for a very long time.
- Started to be less used with the emergence of switching mode power supplies, but nowadays are are still widely used.
- In addition to their simplicity of use, linear regulators have other advantages:
  - Cheap, require few and cheap external components
  - Simple to design circuits
  - Several protection features, low noise, low ripple, fast transient response, ...

BUT they have a significant power dissipation, due to the pass transistor that operates in linear mode.

$$\eta \simeq \frac{V_o}{V_{IN}}$$

E.g. if the input is 12V and output is 3.3V, the linear regulator efficiency is ...

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Only 27.5%. **72.5% of the energy is dissipated as heat!**

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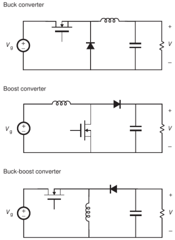
Motivation

Why another type of regulator? Simple - EFFICIENCY!

- Linear regulators can have very low efficiency (see the example before - 25% - but can be less)
- Switching regulators can attain efficiencies higher than can reach 90% to 95%



Source: Robert W. Erickson, DC-DC Power Converters

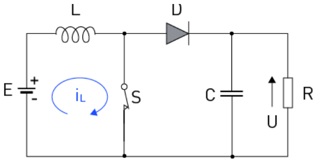
Switching converters - types principles of operation

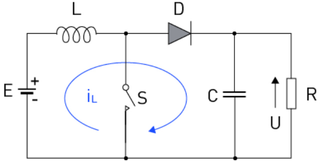
There are several types of DC-DC converters, each with distinct circuit topologies and characteristics.
Non-isolated converters (no galvanic isolation between input and output) are the more common type in micro-electronics, so we will keep the focus on these. The more common topologies are:

- Buck Converter (Step-Down Converter): steps down the input voltage to a lower output voltage while increasing the output current. Used in applications that require a lower voltage level than the input supply, such as battery-powered devices and voltage regulation in computer systems.
- Boost Converter (Step-Up Converter): steps up the input voltage to a higher output voltage while decreasing the output current. Boost converters are commonly used in applications requiring a higher output voltage than the input supply, such as power LED drivers or voltage boosting for portable devices.
- Buck-Boost Converter: versatile topology that can step up or step down the input voltage, depending on the duty cycle of the switches. Buck-boost converters are used in applications such as solar power systems and battery-powered devices with fluctuating voltage levels.

Boost converters - principle of operation

Boost/Step-Up Converter

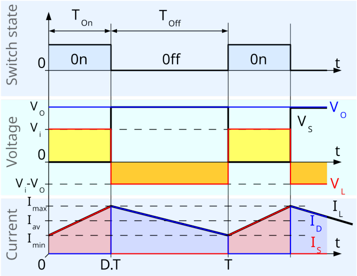




- Switch S turned On
  - D inversely polarized (note the capacitor at the output)
  - Voltage across L is *E*, and the current that flows across it grows linearly
- Switch S turned Off
  - L's magnetic field reduces its energy to maintain the current through it
  - Voltage across L is reversed
  - Current now flows through D (to C and R) that becomes directly polarized
  - Voltage across L adds to E (thus the "Boost")

Boost converters - principle of operation

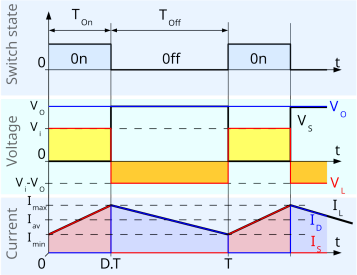
Boost/Step-up Converter



- Switch S is turned On/Off cyclically
- If the cycle is fast enough, the inductor will not discharge fully and the load will always see a voltage greater than that of the input source
- Note that while the switch is opened the capacitor keeps the voltage across the load and the diode block the discharge of C across the switch

Boost converters - principle of operation

Boost/Step-up Converter



In the steady state, the average voltage across the inductor must be zero to allow the inductor to return to the same state after each cycle (remember that the voltage across an inductor is proportional to the rate of change of the current that crosses it).

Considering that D is the duty-cycle of a PWM signal:

$$E \cdot T_{on} = (U - E) \cdot T_{off}\text{, so}$$

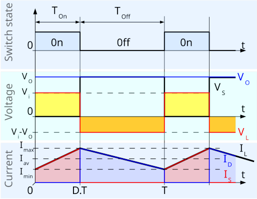
$$U = E\,\frac{1}{1-D}$$

Boost converters - operating modes

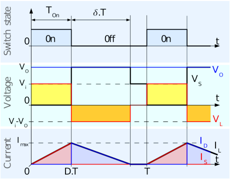
Boost converter - operating modes

There are two operation modes, that affect the behavior of inductor current and impact on the converter's performance, efficiency, and design criteria.

- Continuous Conduction Mode (CCM): The inductor current remains positive and never reaches zero throughout the switching cycle.
  - Lower peak currents and output voltage ripple
  - More efficient and reduces strain on the electronic components
  - BUT requires a bigger inductor
- Discontinuous Conduction Mode (DCM): the inductor current drops to zero, meaning that the energy transfer to the output is finished before the start of the subsequent switch-on period.
  - Smaller inductor, more compact and cheaper
  - BUT larger peak currents, higher output voltage ripple and lower efficiency

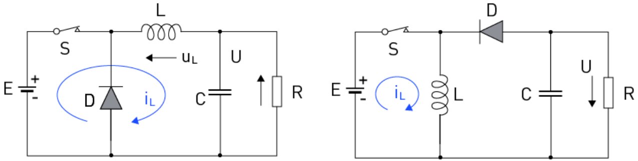


CCM mode



DCM mode

Other converter types



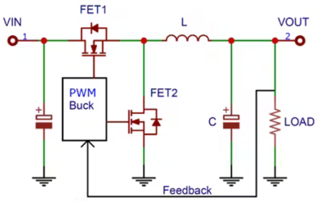
Buck converter and Buck-Boost converter

- There are several other converter types:
  - Buck: Step Down
  - Buck-Boost: Step-up or step-down according with Duty-Cycle
  - and others.

  They work or similar principles, reason why will not be discussed in detail

Practical aspects

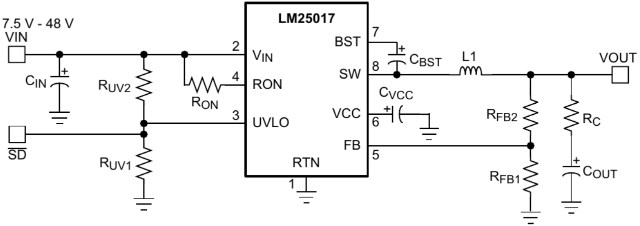
- Switching DC-DC converters need to have a control loop, because the external conditions are often dynamic: the voltage source varies over time, the output current/load varies, etc.



- V_{out} is sampled ("Feedback line in the figure")
- A controller adjusts the PWM duty-cycle according to the error
- The controller output is applied to the "switch"(FET1 in the case)
- In the example there is a synchronous rectifier (FET2), also controlled by the "PWM Buck" control block.

Practical aspects

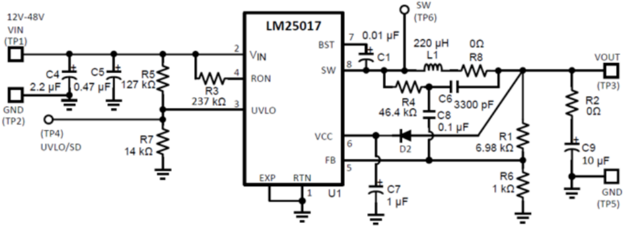
- Example: The LM25017 device is a 48-V, 650-mA synchronous step-down regulator with integrated high-side and low-side MOSFETs



Source: LM25017 datasheet

- Contains an 1.225 V internal reference. "FB" pin is compared with this reference.
- Thus RFB1 and RFB2 allow to control the output voltage: $V_{out} = V_{ref} \frac{RFB1+RFB2}{RFB1}$
- These controllers usually have additional functionalities such as low-voltage detection (UVLO pin), thermal protection, overcurrent, soft start, etc.

Practical aspects



Source: LM25017 datasheet

- Full schematic, as indicated in the datasheet
- There are several configurations. The one in the schematic minimizes the ripple
- The datasheet provides indications to compute the values of R, L and C, to assure stability

Types of voltage sources

Power

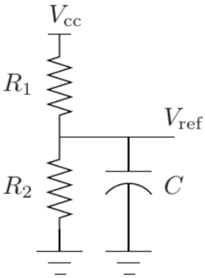
- Do not need to be accurate, as electronic circuits should not depend on a precise value for supply voltage
- Should not present significant and rapid variations (PSRR)
- Should provide “high” output power
- Know as **Voltage Regulators“,**

Signal

- Must be accurate, as they are in the signal path - any error is directly reflected in the output
- Usually do not have special requirements on power or current to be delivered
- Should be independent of ”external“ factors, such as supply voltage variations, temperature variations, etc.
- Know as **Precision Voltage References**
- **Focus of this section**

Precision Voltage References

Precision Voltage Reference - voltage divider

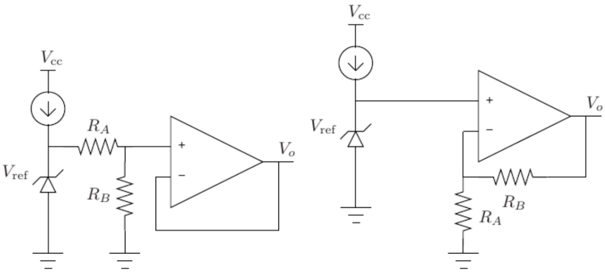


Naive approach - voltage divider

- Simple solution, but ...
- Variations in supply voltage appear at the output, with the same relative magnitude

Precision Voltage References

Precision Voltage Reference - Zener diode

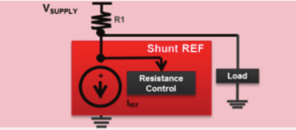


A better circuit

- Better than a voltage divider, but ...
- Relatively high tolerance (5% typ)
- Characteristics vary with temperature

Precision Voltage References

Precision Voltage Reference - dedicated circuits

	Series References	Shunt References
Diagram		
Number of Terminals	At least 3	At least 2
Advantages	• Significantly lower power dissipation • Generally higher precision • Low I_Q • Low dropout	• Wide V_{IN} tolerant with proper resistor selection • Can be used to create negative or floating reference voltages • Inherent current sourcing and sinking
Disadvantages	• Limited max V_{IN}	• V_{IN} current fixed at max load • No shutdown mode
Key Markets	• Factory Automation, Grid, Medical, Test	• Isolated power supplies, Adapters, Automotive
TI Nomenclature	• LM41xx, REFxxxx	• LM40xx-N, LM(V)431, LM1/2/385, LM1/2/336 • ATL431, TL(V)431

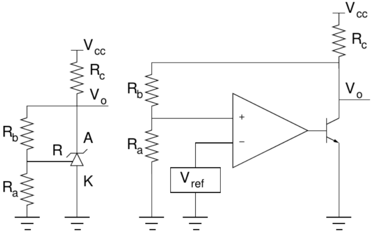
Jocelyn Chang (Ed.). (2017). Tips and tricks for designing with voltage references (No. SLYC147). Texas Instruments.

Dedicated ICs

- Precision voltage reference ICs offer much better performance
- E.g. TL431 (0.5% tolerance, temperature drift of 6mV/K)

Precision Voltage References

Precision Voltage Reference - adjustable sources

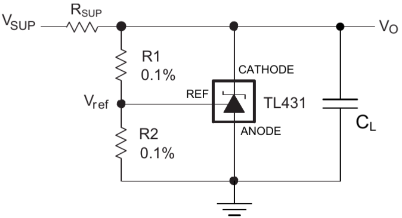


TL431

- Some precision voltage sources are adjustable
- E.g. TL431: $V_o = V_{ref}\left(1 + \frac{R_b}{R_a}\right)$, with $V_{ref} = 2.5\,V$

Precision Voltage References

- Design issues: it in necessary to assure the conditions for the voltage sources to operate correctly.
- These vary with the type of IC (typ. shunt or series): dropout voltage, minimum/maximum current/voltage, etc.



Exercise: design of precision voltage source using a TL431

- The datasheet states that "Sink-current capability: 1 mA to 100 mA"
- Admit that it is pretended to design a voltage reference of 3.5 V, with a supply voltage varying between 4.5 V and 5.5 V. The load can consume between 0 mA 50 mA.
- Compute proper values for R_{SUP}, R_1 and R_2.

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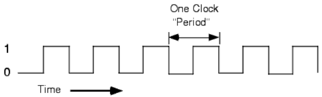
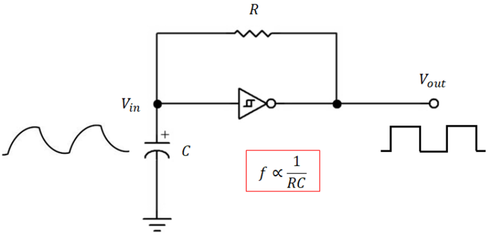
Clock generators



- A clock generator (or simply a "clock" in the jargon) is an electronic oscillator that outputs a clock signal
- Clocks are used to measure time, generate time-related events (e.g. single or periodic interrupts, PWM signals) as well as to synchronize circuit's operation.
- Clock signals can be a simple square wave, but can take more complex forms
- All clock generators integrate a resonant circuit and an amplifier/buffer.
- The resonant circuit is usually based on a quartz piezo-electric oscillator, but there are other possibilities (e.g. simple RC circuits are also widely used).

Clock generators - RC oscillators

Simple RC oscillators: inverter circuit with feedback and an RC network

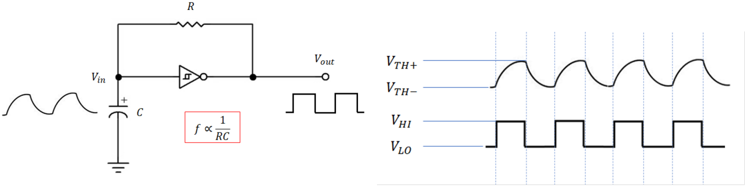


Source: Cadence PCB Solutions, Schmitt Trigger Oscillators: A Simple Square Wave Generator

- Schmitt Trigger Inverter is a "not gate" with hysteresis
- Frequency is proportional to the inverse of the time constant. However, the actual value depends on a few other parameters
- Note that when the circuit boots the output of the nor gate is "on" or "off"

Clock generators - RC oscillators

Simple RC oscillators: inverter circuit with feedback and an RC network

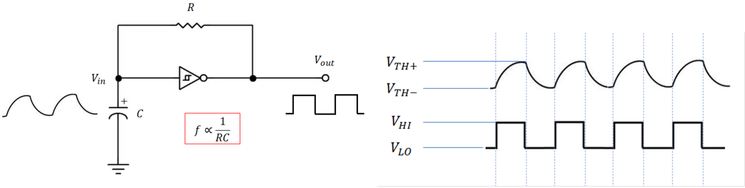


Source: Cadence PCB Solutions, Schmitt Trigger Oscillators: A Simple Square Wave Generator

- Remember that when a RC network is subject to a step input with voltage values V_I and V_F (initial and final, resp.), the voltage at its terminal is:
  $V_c(t) = V_I e^{-\frac{t}{RC}} + V_F \left(1 - e^{-\frac{t}{RC}}\right)$
- Note that the threshold voltages of the Schmitt Trigger are V_{TH+} and V_{TH-}

Clock generators - RC oscillators

Simple RC oscillators: inverter circuit with feedback and an RC network

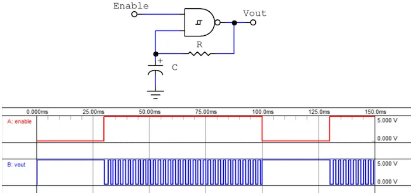


Source: Cadence PCB Solutions, Schmitt Trigger Oscillators: A Simple Square Wave Generator

- Assuming that $V_{LO} = 0V$ (other values can be used by making $V_{HI} = V_{HI} - V_{LO}$, we have:
- $T_{high} = RC \ln(\frac{V_{HI} - V_{TH-}}{V_{HI} - V_{TH+}})$
- $T_{low} = RC \ln(\frac{V_{TH+}}{V_{TH-}})$
- And the period is $T = T_{high} + T_{low}$
- Note that the duty cycle may not be 50%

Clock generators - Quartz crystal oscillators

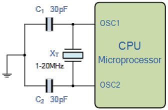
RC-based oscillators: evaluation



- RC-based oscillators are cheap and can be designed to exhibit low energy consumption
  - E.g. many micro-controllers have internal RC oscillators used for low-power modes
- BUT ...
- Its accuracy and stability is poor: frequency varies with temperature, age, supply voltage, load, etc.

Clock generators - Crystal oscillators

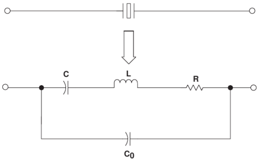
Crystal oscillators

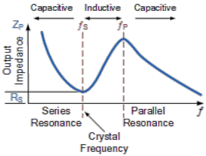


- Crystal oscillators are an electronic oscillator circuit that uses a piezoelectric crystal as a frequency-selective element
- Provide a stable clock signal, being commonly used in many digital applications, such as integrated circuits, radio transmitters and receivers, wristwatches, etc.
- The most common type of piezoelectric resonator used is a quartz crystal. However, other piezoelectric materials (e.g. polycrystalline ceramics) are also commonly used

Clock generators - Crystal oscillators

Crystal oscillators - working principle





- A quartz crystal can be modeled as series RLC circuit (models the mechanical vibrations of the crystal), in parallel with a capacitance (Cp, that models the electrical connections to the crystal).
- Crystals have a series resonance (where C resonates with inductance L) at the crystals operating frequency - crystals "series frequency", fs.
- There is a second frequency point established, as a result of the parallel resonance created when L and C resonates with the parallel capacitor (C_O)
- Oscillators can be built to operate either in the series or parallel resonance region

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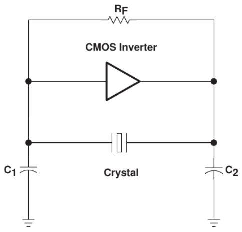
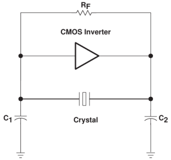
Crystal oscillators - Pierce oscillator



- There are many circuits that can be used to generate a clock form a crystal
- The Pierce oscillator is the more popular because of its reduced parts
- R_f has a very high value (typ. $M\Omega$) and is necessary to bias the input stage of the NOT gate (that acts as an high gain amplifier)
- It is common to see an additional inverter at the output buffering purposes

Clock generators - Crystal oscillators

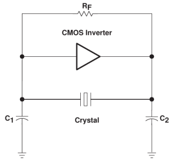
Crystal oscillators:
- Pierce oscillator



- R usually is very low and can be neglected for the analysis
- Under this assumption, $Z = \frac{j}{w} \frac{w^2 LC - 1}{(C_O + C) - (w^2 LCC_O)}$
- The series ressonance frequency is $f_{ser} = \frac{1}{2\pi\sqrt{LC}}$
- And the parallel ressonance frequency is $f_{par} = \frac{1}{2\pi\sqrt{LC}}\sqrt{1 + \frac{C}{C_O}}$
- But ...
  - At series ressonance the impedance of the crystal is very low (just R) and thus the feedback network (i.e. the crystal) impedance mismatches the high impedance of the inverter
  - And parallel ressonance frequency depends on C_O which is a parasitic parameter, as well as other external capacitances, penalizing stability ...

Clock generators - Crystal oscillators

Crystal oscillators:
- Pierce oscillator



- If one (or more) external capacitor(s) are connected in parallel with the crystal (say C_P), the parallel ressonance frequency becomes:
    - $f_{par} = \frac{1}{2\pi\sqrt{LC}}\sqrt{1+\frac{C}{C_P+C_O}}$
- By choosing C_P much bigger than C and C_O we have that $f_{par} \approx \frac{1}{2\pi\sqrt{LC}}(= f_{ser})$
    - Parallel ressonance (that provides a suitable impedance) depends (essentially) in crystal internal parameters
- C_O is typ. 3 pF to 5 pF, and C_P typically is 30 pF. Crustal datasheet should be checks, as it affects the stability.

A good explanation on this topic can be found in TI's Application Report SZZA043, Moshiul Haque and Ernest Cox, "Use of the CMOS Unbuffered Inverter in Oscillator Circuits"

Table of contents

Main bibliography

- Monolithic Power Systems, DC-DC Converters (https://www.monolithicpower.com/en/learning/mpscholar/power-electronics/dc-dc-converters, available 2/9/2024)
- DC-DC Power Converters, Robert W. Erickson, Department of Electrical and Computer Engineering University of Colorado Boulder, CO 80309-0425
- DC-to-DC Converters: Functions, Common Types & Design Principles, Applications, and Challenges, Timur Yuldashev, Andrey Solovev (https://www.integrasources.com/blog/dc-dc-converters-functions-types-design-applications-challenges/, available 2/9/2024)
- Cadence PCB Solutions, Schmitt Trigger Oscillators: A Simple Square Wave Generator. (https://resources.pcb.cadence.com/blog/schmitt-trigger-oscillators-a-simple-square-wave-generator-2, available 10/09/2024)
- Cadence PCB Solutions, RC-Phase Shift Oscillators Using Op-Amps, (https://resources.pcb.cadence.com/blog/2023-cadrc-phase-shift-oscillators-using-op-amps, available 10/09/2024)
- Moshiul Haque and Ernest Cox, "Use of the CMOS Unbuffered Inverter in Oscillator Circuits", TI's Application Report SZZA043
- Ashish Kumar and Pushek Madaan, Cypress Semiconductor, Oscillators: How to generate a precise clock (https://www.edn.com/oscillators-how-to-generate-a-precise-clock-source/, available 11/10/2024)
- Universidade de São Paulo, Digital Electronics, Lecture 4 - Crystal Oscillators (https://edisciplinas.usp.br/pluginfile.php/4840418/mod_resource/content/1/Crystal%20Oscillators.pdf, available 11/09/2024)