# Rectifier circuits for electromagnetic energy collection

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30 oct 2018

# Content

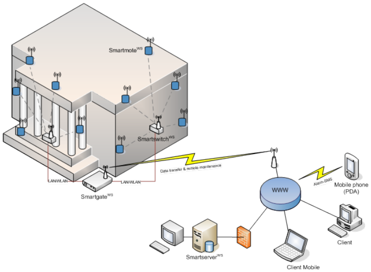
Energy harvesting is a fundamental technology for *smart environments* and the future of secure and reliable machinery [1, 2].

Wireless power transfer (WPT) guarantees energy availability by providing a constant power source [3].

The main applications of WPT are:

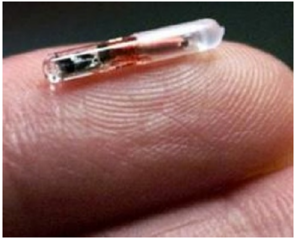
- Wireless sensor networks [4, 5].
- RFID [6].
- Medicine [4, 6].
- Consumer electronics [7].
- Automation, enterprise and domestic security.

- Variable monitoring.
- Structural integrity.
- Instantaneous variables.



The main applications of WPT are:

- Wireless sensor networks [4, 5].
- RFID [6].
  - Transportation.
  - Inventory.
  - Localization.
  - Existence.
- Medicine [4, 6].
- Consumer electronics [7].
- Automation, enterprise and domestic security.

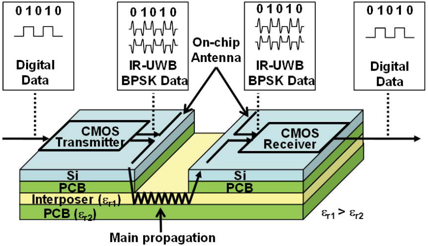


The main applications of WPT are:

- Wireless sensor networks [4, 5].
- RFID [6].
- Medicine [4, 6].
  - People and equipment tracking.
  - patients monitoring and treatment.
  - Control of robotic prosthetics.
- Consumer electronics [7].
- Automation, enterprise and domestic security.

The main applications of WPT are:

- Wireless sensor networks [4, 5].
- RFID [6].
- Medicine [4, 6].
- Consumer electronics [7].
  - Short distance fast speed communications.
  - Electrical isolation in power stages.
- Automation, enterprise and domestic security.



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- Automation, enterprise and domestic security.

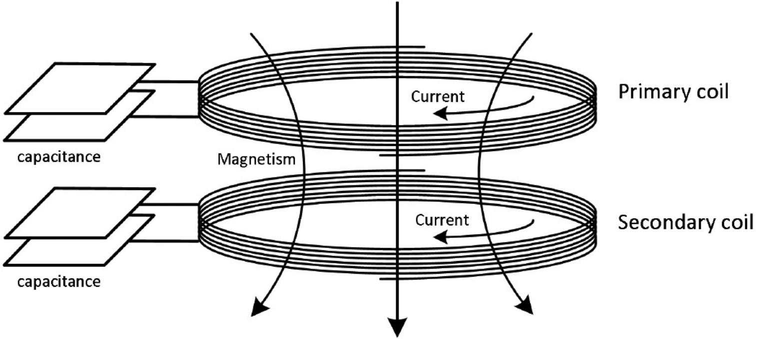
*The internet of things*

Wireless power transfer (WPT) is divided in 2 categories: near-field (inductive) transfer and far-field (electromagnetic) transfer [8].

Near-field is defined as [9]:

$$d < 0.62\sqrt{\frac{D^3}{\lambda}}$$

$d$: transmission distance,
$D$: maximum transmitter size,
$\lambda$: wavelenght.



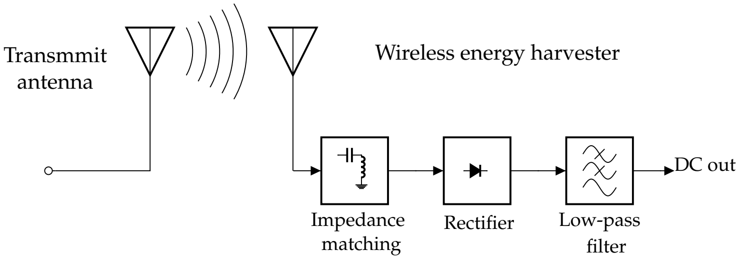

Near Field power transfer.

Wireless power transfer (WPT) is divided in 2 categories: near-field (inductive) transfer and far-field (electromagnetic) transfer [8].

Far-field is defined as [9]:

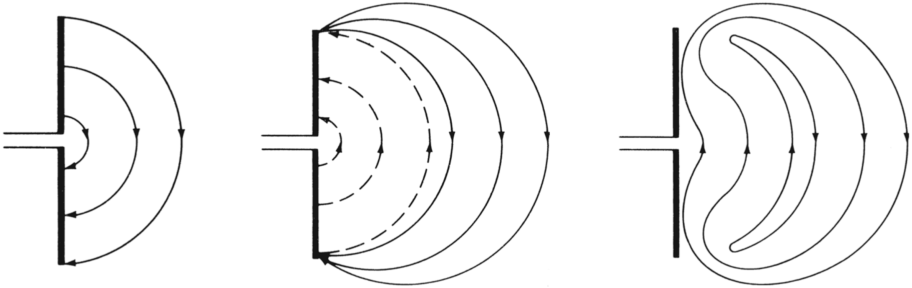
$$d > 2\frac{D^2}{\lambda}$$

$d$: transmission distance,
$D$: maximum transmitter size,
$\lambda$: wavelenght.




Far Field power transfer.

Antennas allow the transduction of electric power into electromagnetic waves [9].



The transmission and reception characteristics are equal.

Friis' equation relates the transmitted and received power between 2 antennas.

$$\frac{P_r}{P_t} = e_{cdt} e_{cdr} (1 - |\Gamma_t|^2)(1 - |\Gamma_r|^2) \left( \frac{\lambda}{4\,\pi\,R} \right)^2 D_r(\theta_r, \phi_r) D_t(\theta_t, \phi_t) |\hat{\boldsymbol{\rho}}_w \cdot \hat{\boldsymbol{\rho}}_a|^2$$

Radiation loss is $\propto \dfrac{1}{R^2}$ and represents the main cause of energy losses.

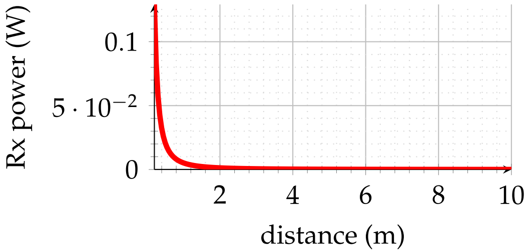
Friis' equation relates the transmitted and received power between 2 antennas.

$$\frac{\overbrace{P_r}^{\text{Rx power}}}{\underbrace{P_t}_{\text{Tx power}}} = \overbrace{e_{cdt}}^{\text{Tx eff}} \underbrace{e_{cdr}}_{\text{Rx eff}} \overbrace{(1 - |\Gamma_t|^2)}^{\text{Tx Z match}} \underbrace{(1 - |\Gamma_r|^2)}_{\text{Rx Z match}} \overbrace{\left(\frac{\lambda}{4\,\pi\,R}\right)^2}^{\text{Rad loss}} \underbrace{D_r(\theta_r, \phi_r) D_t(\theta_t, \phi_t)}_{\text{directivity loss/gain}} \overbrace{|\hat{\boldsymbol{\rho}}_w \cdot \hat{\boldsymbol{\rho}}_a|^2}^{\text{polarization loss}}$$

Radiation loss is $\propto \frac{1}{R^2}$ and represents the main cause of energy losses.

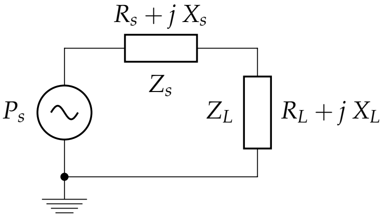
A simplified Friss' equation for practical purposes is:

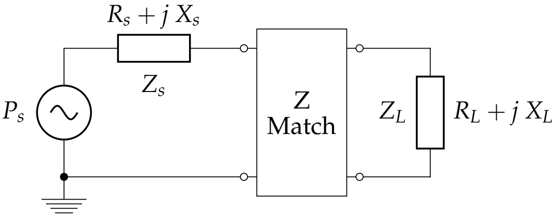
$$P_r = EIRP_t\, e_{cdr}(1 - |\Gamma_r|^2)\left(\frac{\lambda}{4\,\pi\,R}\right)^2 D_r(\theta_r, \phi_r)|\hat{\boldsymbol{\rho}}_w \cdot \hat{\boldsymbol{\rho}}_a|^2$$



# Impedance Matching

Maximum power will be transferred from a source to its load if the **load impedance equals the source impedance** [10].



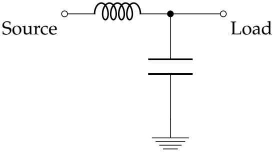

$$R_s + j\,X_s = R_L + j\,X_L$$

$$R_s + j\,X_s \neq R_L + j\,X_L$$

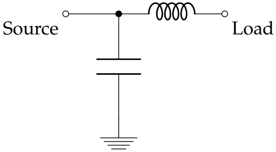
Matching networks are designed for a determined frequency and bandwidth.

# Impedance Matching

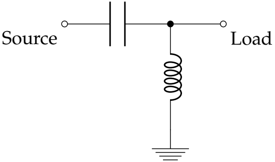
For low loss in RF harvesting systems the L matching network is the adequate choice [11].



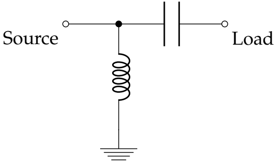

a) Low-pass, Higher Z




b) Low pass, Lower Z up




c) High pass, Higher Z




d) High pass, Lower Z

$$Q_s = Q_p = \sqrt{\frac{R_p}{R_s} - 1}$$

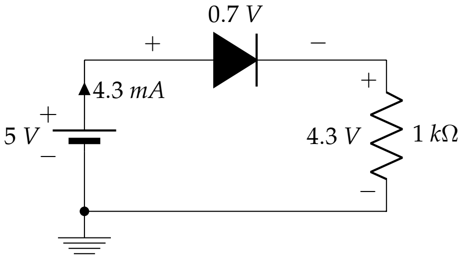
$$Q_s = \frac{X_s}{R_s}$$

$$Q_p = \frac{R_p}{X_p}$$

Subindex $p$ represents parallel component and subindex $s$ represents series component.

Nonlinearities represents the main problem when analyzing rectifier circuits.

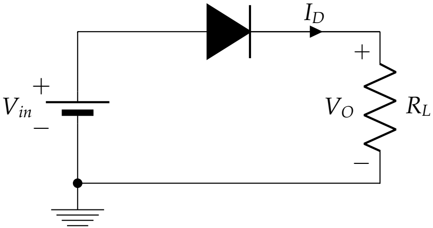
A basic analysis assumes a constant $V_{th}$.




$$V_R = V_{in} - V_D$$

$$I = \frac{V_R}{R}$$

A better approach would consider the diode current-voltage relationship.

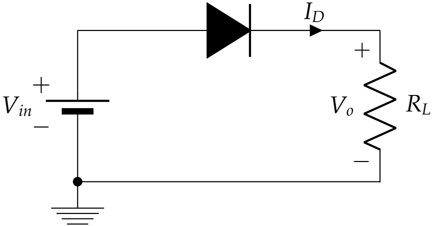


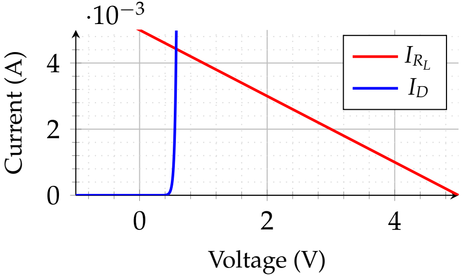

$$I_D = I_S \left( e^{\frac{V_D}{n\frac{kT}{q}}} - 1 \right)$$

where:

| | |
|---|---|
| $V_D$ | diode voltage ($V$), |
| $I_D$ | diode current ($A$), |
| $I_S$ | diode saturation current ($A$), |
| $n$ | ideality factor 1 - 2, |
| $k$ | Boltzmann constant, |
| $T$ | temperature ($K$), |
| $q$ | electron charge |

The solution may be found with any numerical method.

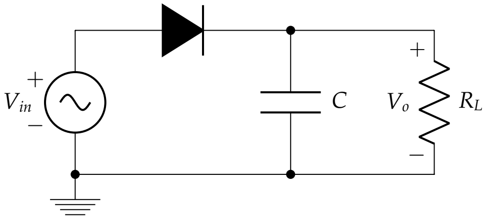


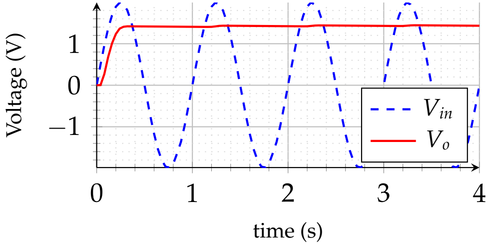




$$I_{R_L} = \frac{V_{in}}{R_L} - \frac{V_o}{R_L} = I_D = I_S \left( e^{\frac{V_{in} - V_o}{n \frac{kT}{q}}} - 1 \right)$$

A closed form solution is also possible [12].

Considering an AC input requires frequency response considerations.



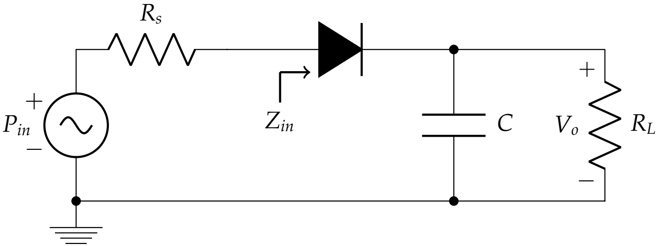




$$I_D\left(V_{in}(t) - V_o(t)\right) = C\frac{\mathrm{d}V_o(t)}{\mathrm{d}t} + \frac{V_o(t)}{R_L}$$

y

$$V_{in}(t) = V_p \sin(\omega\, t + \phi)$$

A non-controlled power input complicates the problem even further.




$$I_D\Big(V_{in}(t) - V_o(t)\Big) = C\frac{\mathrm{d}V_o(t)}{\mathrm{d}t} + \frac{V_o(t)}{R_L}$$

y

$$V_{in}(t) = V_p \sin(\omega\, t + \phi), \qquad V_P = 2\,\sqrt{2\,R_s P_{in}}\,\frac{Z_{in}}{R_s + Z_{in}}$$

SPICE is the preeminent electronic circuit simulator. The analysis types for RF rectifiers are:

- Transient
- AC
- Harmonic Balance
- Shooting Methods

Time domain:

- Uses the **Modified Nodal Analysis** method.
- Provides the complete time-domain response of the circuit.
- May be used to optimize the desired system response.
- Computationally heavy for circuits with long stabilization periods.

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Frequency domain:

- Calculates the frequency response of the system.
- May be used to calculate the steady state linear transfer parameters (Z, Y, H, S).
- Useful for obtaining the bandwidth of the system.

SPICE is the preeminent electronic circuit simulator. The analysis types for RF rectifiers are:

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Frequency/Time domain:

- Calculates the steady state response in the Fourier domain.
- Fast, few harmonics provide a good approximation of the response.
- Limited to sine signals (single or multi tone) and periodic responses.
- Time to reach steady state not available.

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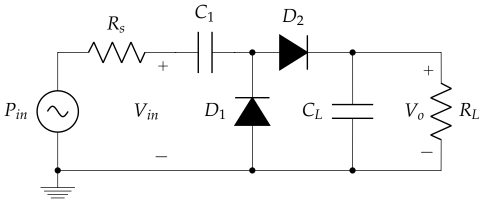
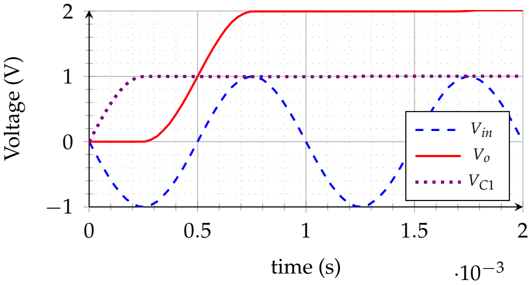
Time domain:

- *Shoots* a prediction of the steady-state conditions of the circuit and iterates.
- In practice is very similar to harmonic balance.

The half-wave voltage doubler is the most ubiquitous type of RF rectifier.




$$V_o = 2\,V_{in} - V_{th1} - V_{th2}$$

Also known as the Greinacher multiplier, is mostly used in cases where information from the RF signal should be extracted.

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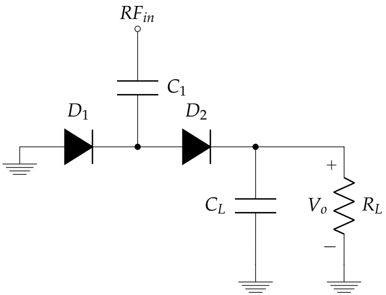
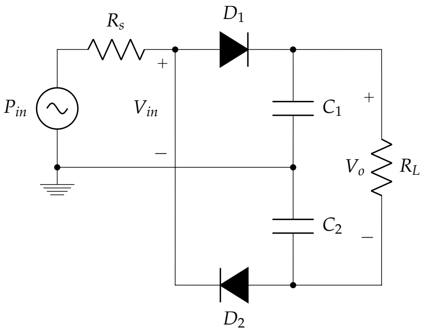


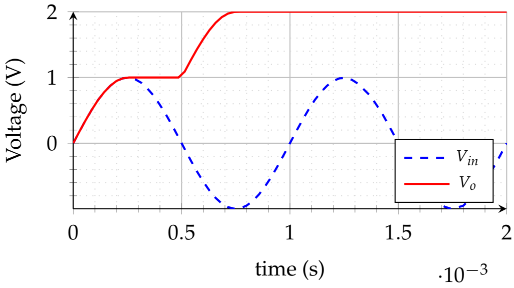

- Blocks DC components due to $C_1$
- Preserves the same GND terminal as the source, even for multiple stages.
- Ideal response time $\frac{3}{4}T$.

$$V_o = 2\,V_{in} - V_{th1} - V_{th2}$$

Also known as the Greinacher multiplier, is mostly used in cases where information from the RF signal should be extracted.

The full-wave voltage doubler is an alternative to the half-wave doubler.

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In practice, this architecture has a smaller stabilization period compared to the half-wave doubler.

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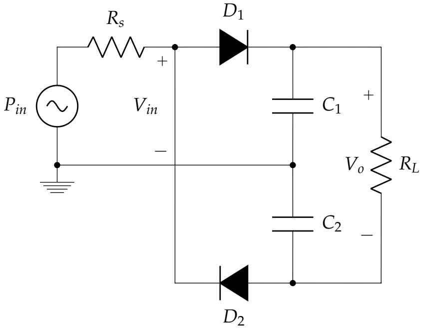
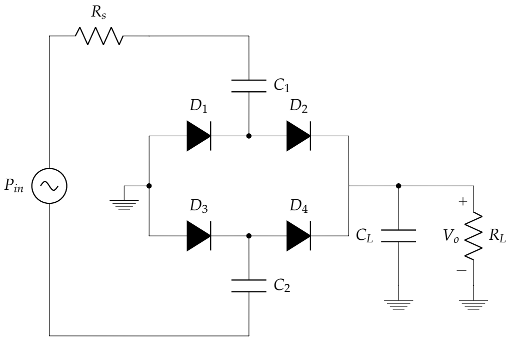


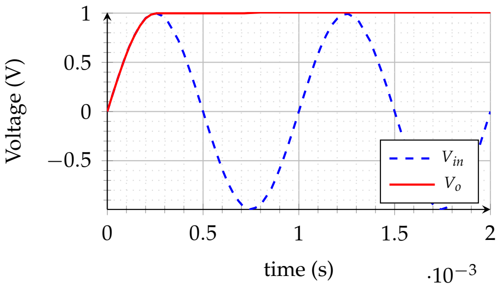

- DC components are not blocked
- GND terminal from source is changed in the output
- Ideal response time $\frac{3}{4}T$.

$$V_o = 2\,V_{in} - V_{th1} - V_{th2}$$

In practice, this architecture has a smaller stabilization period compared to the half-wave doubler.

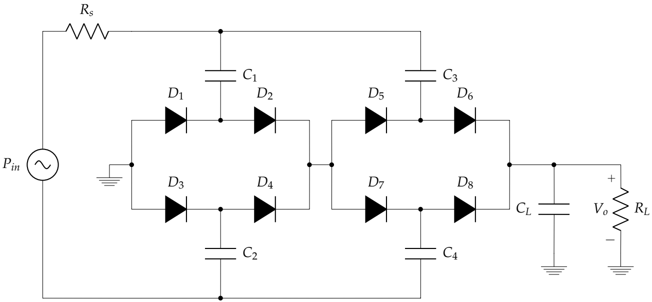
The voltage multiplying bridge is mostly used in RFID applications.

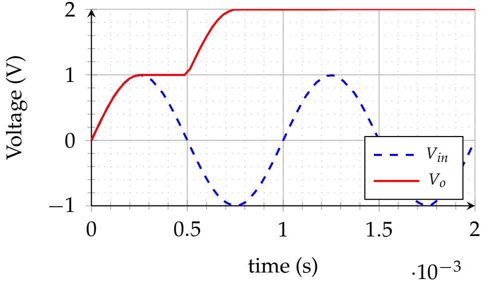



The "modular" characteristics makes it a versatile rectifier.

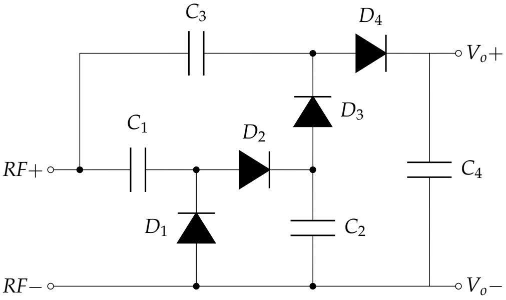
Multiple stages are required for voltage multiplication.



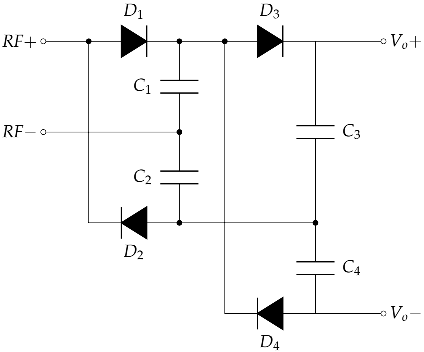




The "modular" characteristics makes it a versatile rectifier.

Generally multiple stages are required to achieve useful power levels.

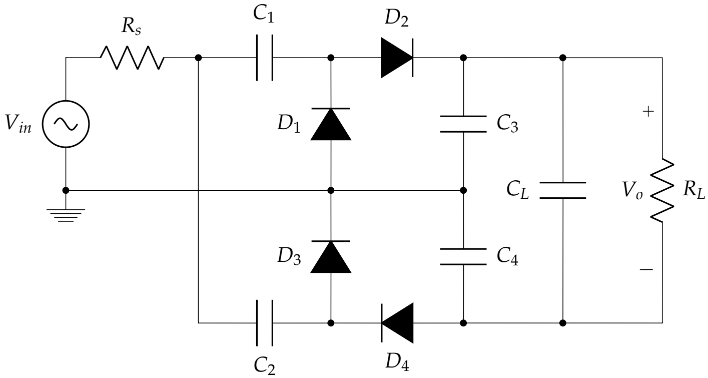



2 stage half-wave voltage multiplier.




2 stage full-wave voltage multiplier.

The *mirror-stacked* configuration is an alternative to multi-staging rectifiers.




It can be used with multiple stages for additional voltage increase.

The two main parameters to measure the performance of a rectifier are:

**Efficiency**:

Is defined as the ratio of RMS AC input power and the DC power absorbed by the load.

$$\eta = \frac{P_{L,DC}}{P_{in,RMS}} = \frac{I_o \cdot V_o}{V_{in,rms} \cdot I_{in,rms}}$$

Transient values may be neglected depending on application.

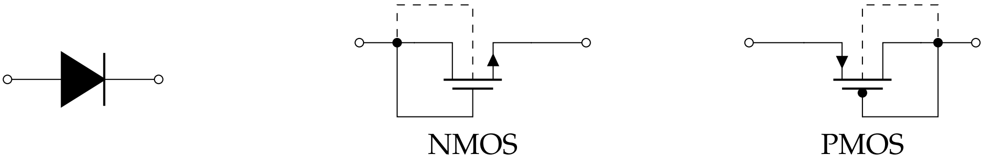
**Sensitivity**:

The minimum input power required to obtain a desired voltage/current output.

# Rectifier
## Diode connected transistors

The main source of energy losses in RF rectifiers is the threshold voltage of the active elements.

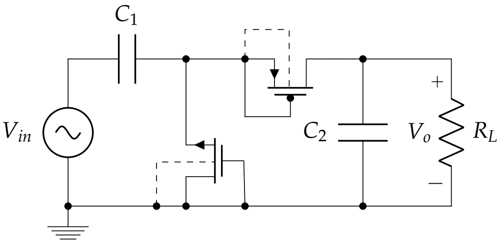
A threshold voltage ($V_{th}$) compensation is possible when MOS transistors are used as rectifiers.



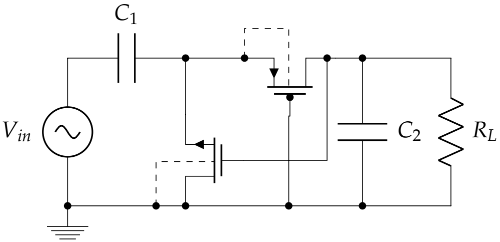

Diode-connected transistors.

The available power is in the rage of $-20\ dBm$ to $0\ dBm$ ($10\ \mu W$ to $1\ mW$).

Self-$V_{th}$ cancelation (SVC) scheme [13] is effective for low input power applications ($\approx -10\ dBm$).



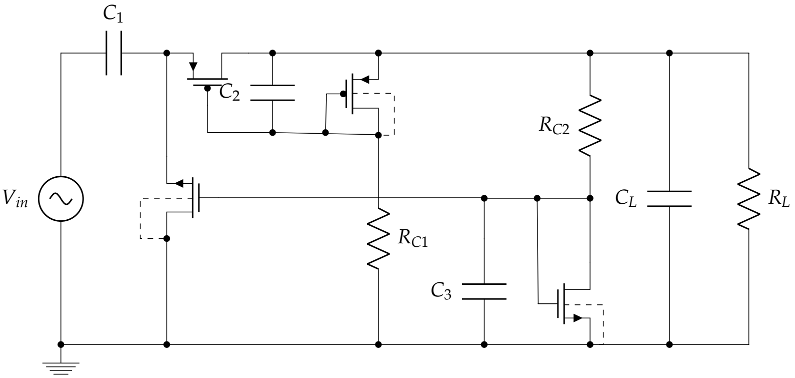

Rectifier without compensation.




Rectifier with SVC scheme.

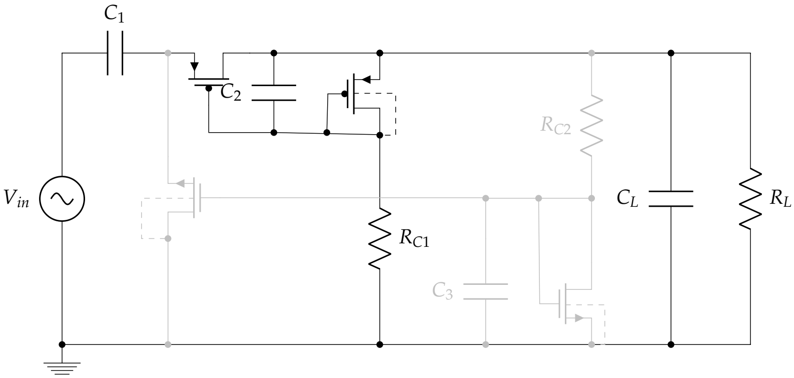
The main purpose is to maintain the gates of PMOS and NMOS transistors to the lowest and highest (respectively) voltage available.

Internal $V_{th}$ cancellation scheme (IVC) [14] is effective for medium to large power inputs ($\approx -3\ dBm$).



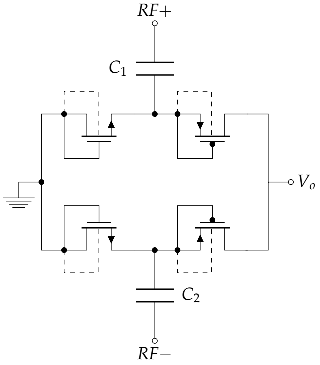

Resistors $R_{C1}$ and $R_{C2}$ are set at at a high value (tens of $k\Omega$) to reduce losses.

Internal $V_{th}$ cancellation scheme (IVC) [14] is effective for medium to large power inputs ($\approx -3\ dBm$).

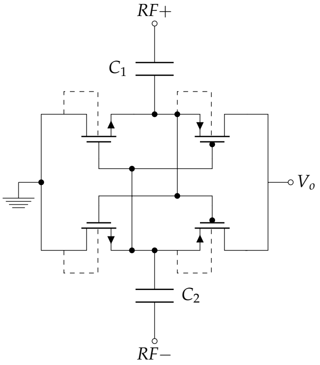



Resistors $R_{C1}$ and $R_{C2}$ are set at at a high value (tens of $k\Omega$) to reduce losses.

The differential drive CMOS rectifier [15] is widely regarded as one of the most advanced rectifiers.

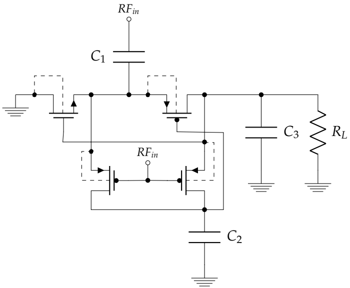



Without compensation

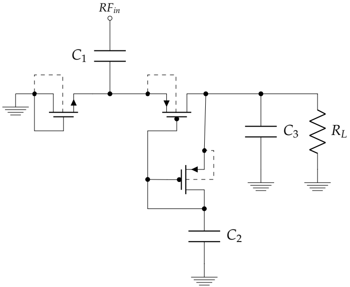



$V_{th}$ compensated.

Other techniques to increase the efficiency of rectifiers involve the reduction of the leakage current.




Threshold voltage and leakage current compensation [16].



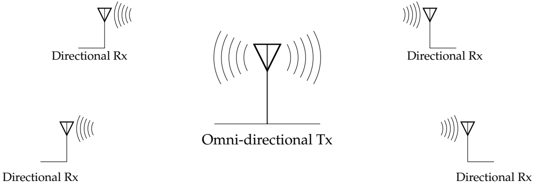

Leakage current compensation [17].

### Operation frequency

- UHF band 850 $MHz$ ($\lambda \approx 0.3527\, m$) [13, 14].
- ISM 433 $MHz$, 2.4 $GHz$ and 5 $GHz$.

### Antenna type

For WSN it is recommended to consider omni-directional antennas for Tx and directive antennas for Rx.




If the antenna is used below its resonant frequency the inductive effect may be used to ease impedance matching.

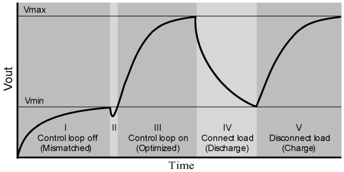
In general WPT may operate in 2 different modes [18]:

**Continuous mode (duplex):**

The system is design to maximize efficiency in **steady-state**. In general, the period to achieve steady state may be relatively large.

**Charge-burst mode (sequential):**

The system is optimized to reduce the **transient response** and only provide power to the load for a very short time [19].



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