Embedded System 1

AA 2020-2021

POLITECNICO DI MILANO

How to provide power to embedded systems

William FORNACIARI

Politecnico di Milano – Dipartimento di Elettronica e Informazione
Milan, Italy

Via Ponzio 34/5 – 20133 Milanom, Italy

william.fornaciari@polimi.it

Power source

- Rechargable batteries

Typical Power Management

- Main functions and architeture
- Portable power systems

Wireless charging

- Architecture
- Standards
- Example of designs

References

Battery-powered Embedded Systems

- Batteries can be used to make objects portable

- This can be done if the energy requirements of the object are compatible with the size of the battery

- Power management assumes a key role in device power consumption, minimizing energy wasting

Rechargeable batteries

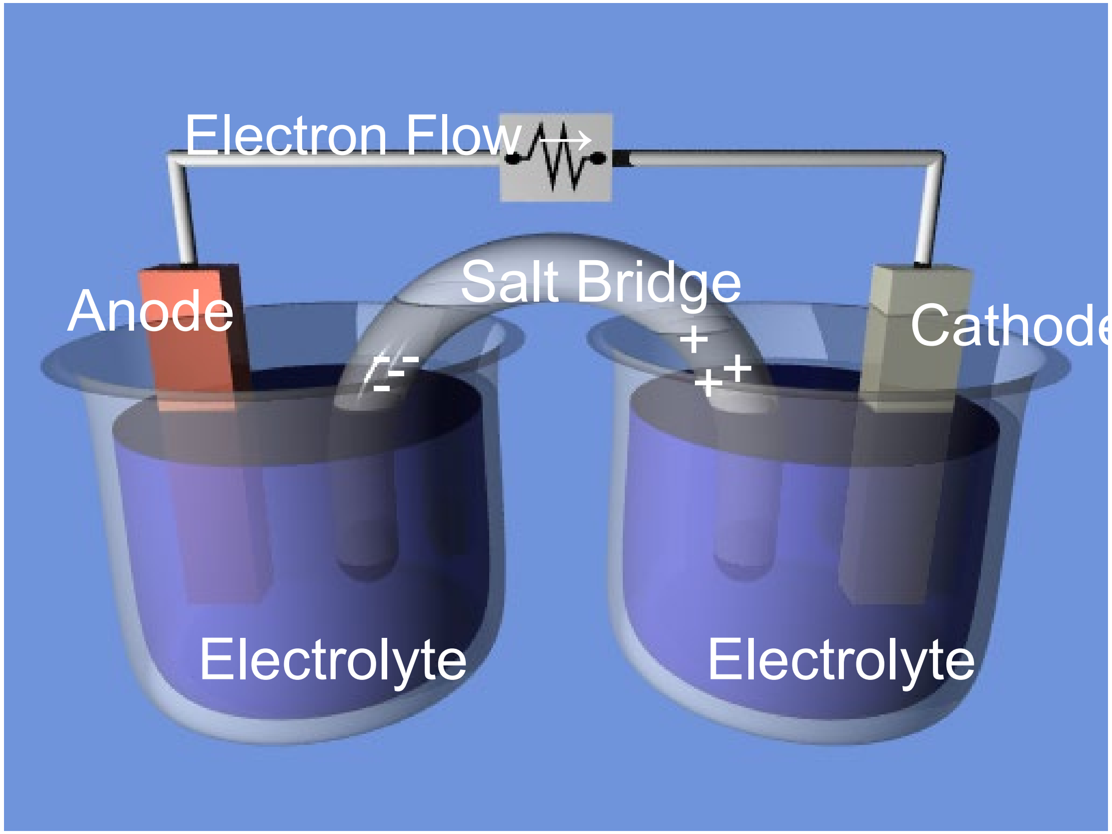
Characteristics to be valuated when choosing batteries

- **Reliability**
- **Capacity (Ah)**
- **Peak current**
- **Temperature range**
- **Efficiency**
- **Charging time**
- **Deterioration**
- **Size**
- **Different form factors**
- **Discharge current (long term)**
- **….COST…**
- **…and COST!!!!**

How Electrochemical Batteries Work

REDOX Reaction

- Oxidation, the loss of electrons, occurs at the anode
- Reduction, the gain of electrons, occurs at the cathode



Electrochemical Battery History

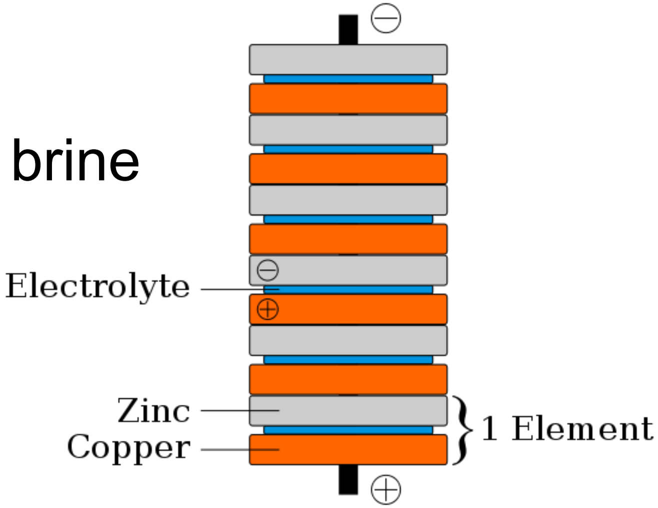
“Baghdad Batteries”

- ~1000-2000 years ago
- Terracotta jars containing a copper cylinder separated from an iron rod by a non-conductive stopper, and filled with an electrolyte
- Debated uses: electroplating, experiencing God

Electrochemical Battery History Cont'd

The Voltaic Pile

- Invented by Alessandro Volta in 1800
- Zinc and Copper with a cloth soaked in brine
- Technical Flaws:
  - Compressing of cloth created shorts
  - Short battery life

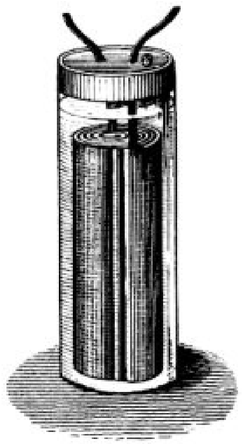


The Daniel Cell

- Invented in 1836 by John Daniell

The lead-acid cell

- Invented in 1859 by Gaston Planté
- First rechargeable battery



The zinc-carbon cell

- Invented in 1887 by Carl Gassner

Electrochemical Battery History Cont'd

The Nickel-Cadmium Battery

- Invented in 1899 by Waldmar Jungner
- Commercial in 1946

The common Alkaline Battery

- Invented in 1955 by Lewis Urry

The Nickel Metal-Hydrid Battery

- NiMH batteries for smaller applications started to be on the market in 1989

Lithium and Lithium-ion Batteries

- First lithium batteries sold in the 1970s
- First lithium-ion batteries sold in 1991
- First lithium-ion polymer batteries released in 1996

Quick Overview of Other Batteries

Mercury Battery

- Shelf life of up to 10 years

Silver-Oxide Battery

- Prohibitive costs, but excellent energy density

Atomic Batteries

- Thermionic Converter
- Thermophotovoltaic Cells
- Reciprocating Electromechanical Atomic Batteries

Betavoltaics

- Use energy from atom decay emitting beta radiation
- Used for remote and long-term needs, e.g. spacecraft

Terminology and Units

Primary Batteries

- Disposable, converts chemical energy to electrical energy **directly**, using the chemical materials within the cell to start the action

Secondary Batteries

- Rechargeable, must first be **charged** with electrical energy before it can convert chemical energy to electrical energy (frequently called **storage battery**)

emf – Electromotive force, voltage

Ampere·hour (Ah)

- 3600 coulombs, a measure of electric charge

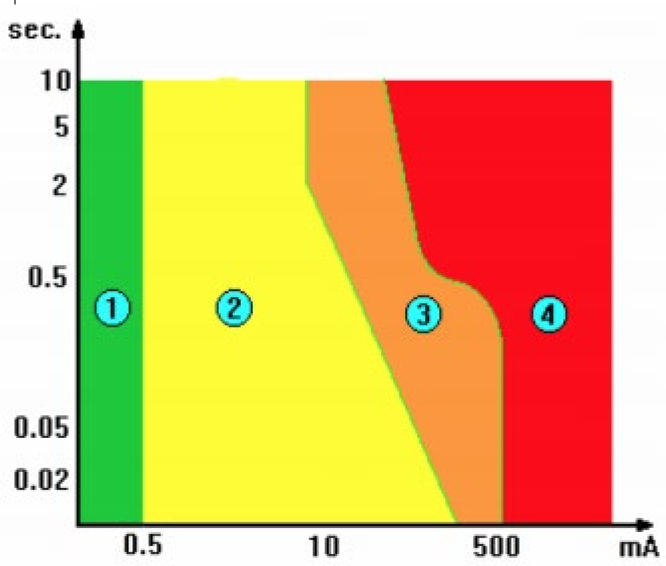
Watt ·hour (Wh)

- 3600 joules, a measure of energy

Ah = (Wh) / emf

Current – always dangerous

Current Amperes	Physiological Phenomena	Effect on Man
< 0.001	None	Imperceptible
0.001	Perception Threshold	Mild Sensation
0.003	Pain Threshold	Painful Sensation
0.010	Paralysis Threshold of Arms and Hands	Person cannot release grip if no grip, victim may be thrown clear. Tighter grip because of paralysis may allow more current to flow; may be fatal.
0.030	Respiratory Paralysis	Stoppage of breathing, frequently fatal.
0.075	Fibrillation Threshold	Heart action uncoordinatec probably fatal.
4.000	Heart Paralysis Threshold	Heart stops on current passage, normally restarts when current interrupted.
5.000	Tissue Burning	Not fatal unless vital organ are burned



Most of your electrical resistance is in your skin

- It varies from 500 ohms (clean) to several million ohms (dirty)
- Inside a tissue is much smaller

Lead Acid Battery

- Electrolyte for the most part distilled (pure) water, with some sulfuric acid mixed with the water
- Electrodes must be of dissimilar metals
- The oxygen and hydrogen gases released during the gassing phase of a typical flooded lead-acid battery recharge can be dangerous if allowed to **exceed 0.8 % (by volume) or 20 percent of the lower explosive range**
- Concentrations of hydrogen between 4 % and 74% are considered explosive (40,000 ppm and 740,000 ppm)

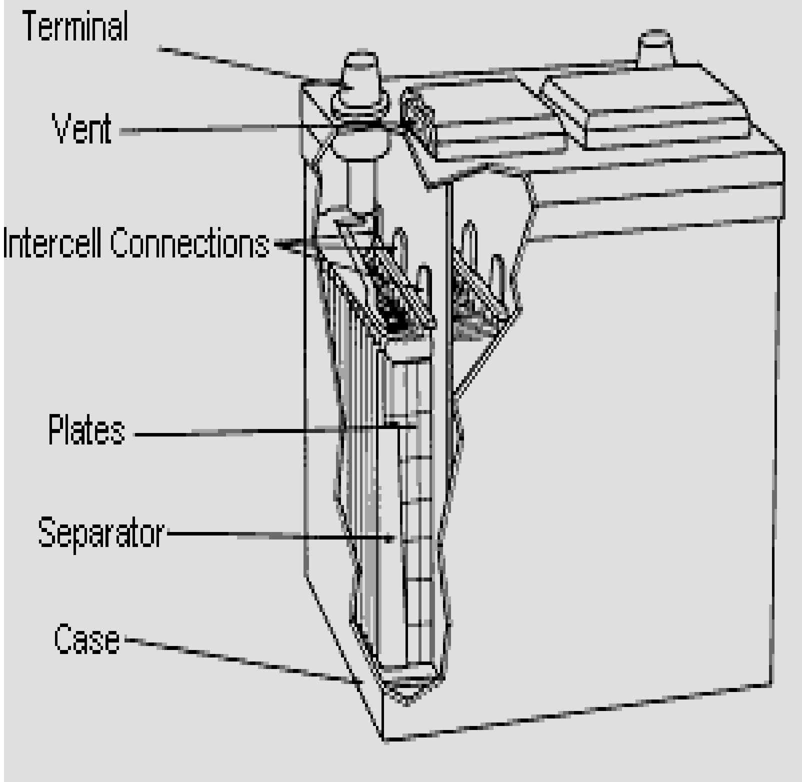
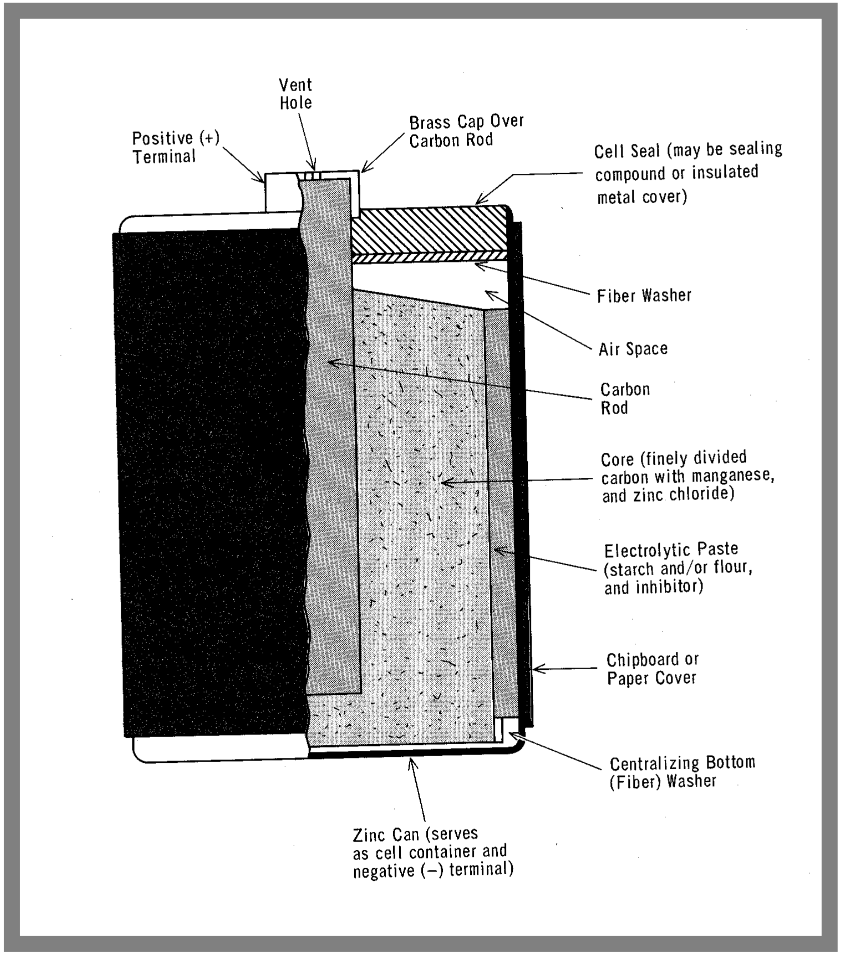


Figure 6 - Flodded Lead-Acid Battery

Dry cell

- Uses An electrolytic paste
- The electrolytic paste reacts with the electrodes to produce a negative charge on one electrode and a positive charge on the other
- The difference of potential between the two electrodes is the output voltage
- Possibility to stay upsidedown



Capacity Rating System

The Society of Automotive Engineers (SAE) has established two ratings for domestic made batteries:

- Reserve Capacity (RC)

  Reserve capacity is the time required (in minutes) for a fully charged battery at 80°F under a constant 25 amp draw to reach a voltage of 10.5 volts

- Cold Cranking Amps (CCA)

  This rating measures the discharge lead (in amps) that a battery can supply for 30 seconds at 0°F (-17°C), while maintaining a voltage of 1.2 volts per cell (7.2 volts per battery or higher)

Primary Alkaline Batteries

Can lose 8 – 20% charge every year at room temperature

Discharge performance drops at low temperatures

	AAA	AA	9V (PP3)	C	D
Capacity (Ah)	1.250	2.890	0.625	8.350	20.500
Voltage	1.5	1.5	9	1.5	1.5
Energy (Wh)	1.875	4.275	5.625	12.525	30.75

Secondary Alkaline Batteries

Self-discharge more quickly than primary batteries

- Energy/volume: 50-150 Wh/L, Energy/weight: 40-60 Wh/kg
- NiMH have a higher capacity, are cheaper, and less toxic than NiCd

	Low-Capacity NiMH (1700-2000 mAh)	High-Capacity NiMH (2500+ mAh)	NiCd
Charge Cycles	1000	500	1000

Pro

- Hard to damage
- High duration (charge/discharge cycles rate)
- Low series resistance (can supply high currents)
- Low degradation when not used

Cons

- Must not overcharge because that will damage the batteries. Quick charges will also damage the batteries. Must not over-discharge
- NiCd has “memory effect”
- NiCd is better for applications where current draw is less than the battery’s own self-discharge rate

Lithium-Ion and Lithium-Ion Polymer Batteries

- Great energy-to-weight ratio (~160 Wh/kg compared to 30-80 Wh/kg in NiMH)
- No memory effect
- Slow self-discharge rate
- Battery will degrade from moment it is made
- Protection circuits are required to protect the battery
- Li-Ion Polymer batteries are significantly improved:
  - Higher energy density
  - Lower manufacturing costs
  - More robust to physical damage
  - Can take on more shapes

Tech Specs

- Energy/volume 250-620 Wh/L
- Energy/weight 100-265 Wh/kg
- Lifetime 400-1200 cycles

- **Pro**
  - Can have different form factors
  - No deterioration due to charge/discharge cycles
  - No memory effect (complete discharge not required)
- **Cons**
  - Ageing from the fabrication time
  - High deterioration due to heat
  - May explode if over-charged or heated (built-in protection circuit)
  - Complete discharges can damage the battery

LI-Po

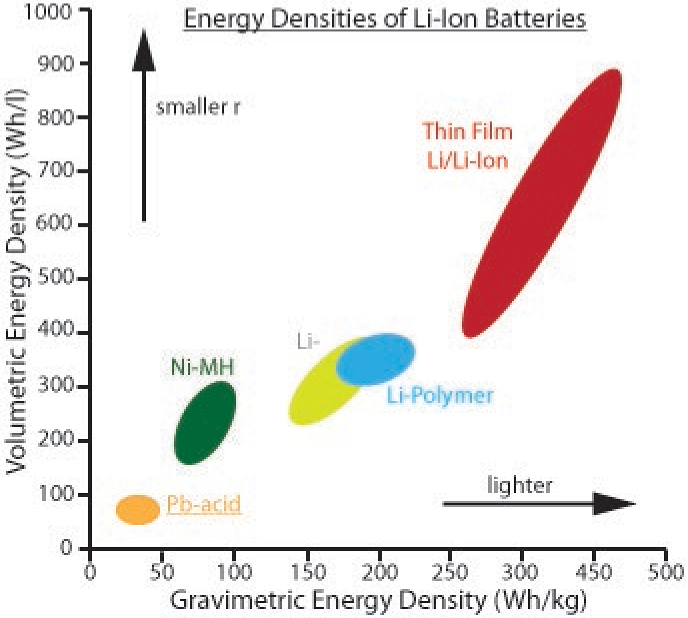
Main features

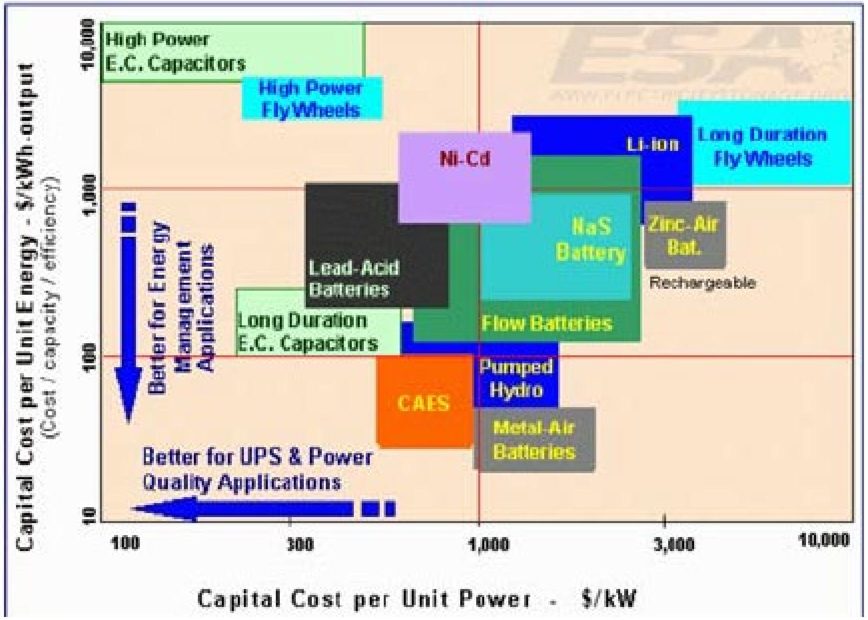
Tech Specs

- Energy/volume 250-730 Wh/L
- Energy/weight 100-265 Wh/kg
- Lifetime 400-100 cycles

- **Pro**
  - Higher energy capacity
  - No memory effect
  - Less degradation compared to Li-Ion batteries
  - Highly shapeable
  - Reduced charge times
- **Cons**
  - Highly flammable when perforated
  - May explode if over-charged or heated (built-in protection circuit)
  - Highly sensitive to charge/discharge cycles

Ragone plots, miscellanea





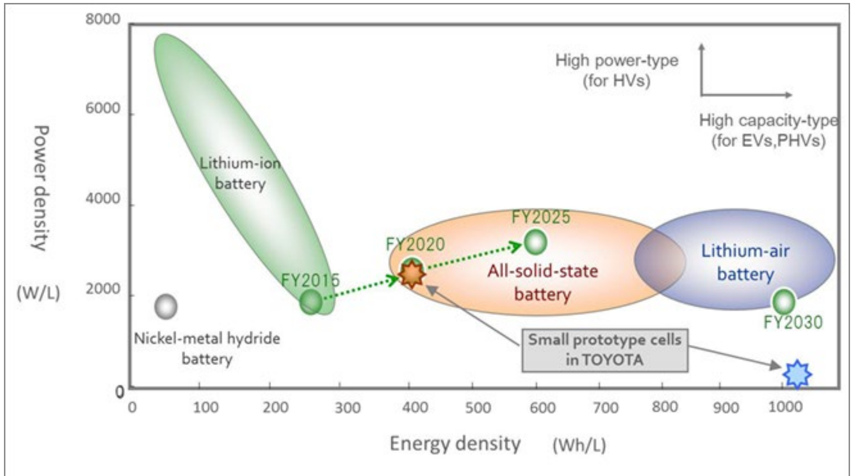
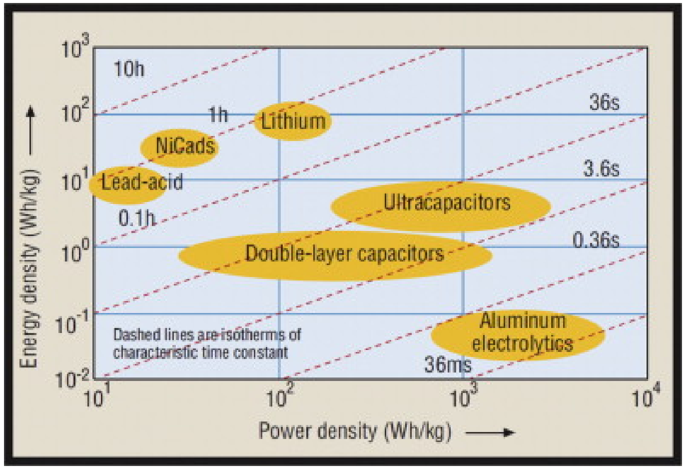


Figure 1. Ragone plots for various battery systems



Other features

Battery chemistry	Rechargeable	Typical self-discharge or shelf life
Lithium metal	No	10 years shelf life[3]
Alkaline	No	5 years shelf life[3]
Zinc–carbon	No	2–3 years shelf life[3]
Lithium-ion	Yes	2–3% per month;[3] ca. 4% p.m.[4]
Lithium-polymer	Yes	~5% per month[5][better source needed]
Low self-discharge NiMH	Yes	As low as 0.25% per month[6]
Lead–acid	Yes	4–6% per month[3]
Nickel–cadmium	Yes	15–20% per month[3]
Nickel–metal hydride (NiMH)	Yes	30% per month[3]

Type		IEC name[10]	ANSI/NEDA name[11]	Typical capacity in mAh	Nominal voltages
Primary (disposable)	Alkaline	6LR61	1604A	550	9
		6LP3146[12]	1604A	550	9
	Zinc–carbon	6F22	1604D	400	9
	Lithium		1604LC	1200	9
Rechargeable	NiCd	6KR61	11604	120	7.2, 8.4
	NiMH	6HR61	7.2H5	175-300	7.2, 8.4, 9.6
	Lithium polymer			520	7.4
	Lithium-ion			620	7.4
	Lithium iron phosphate			200-320	9.6

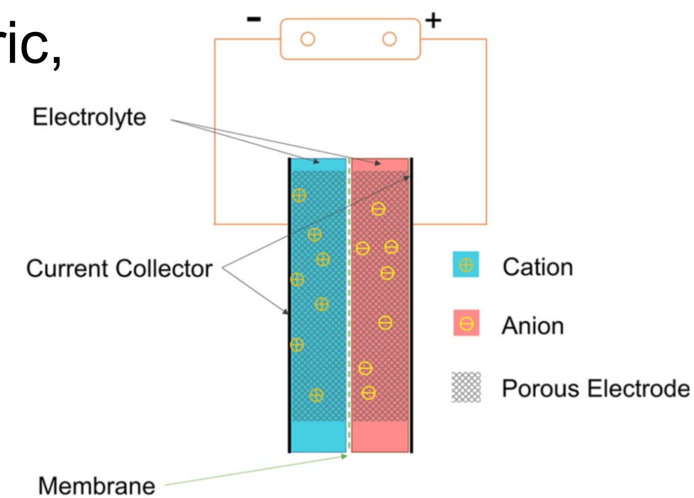
Supercapacitors (or Ultacapacitors)

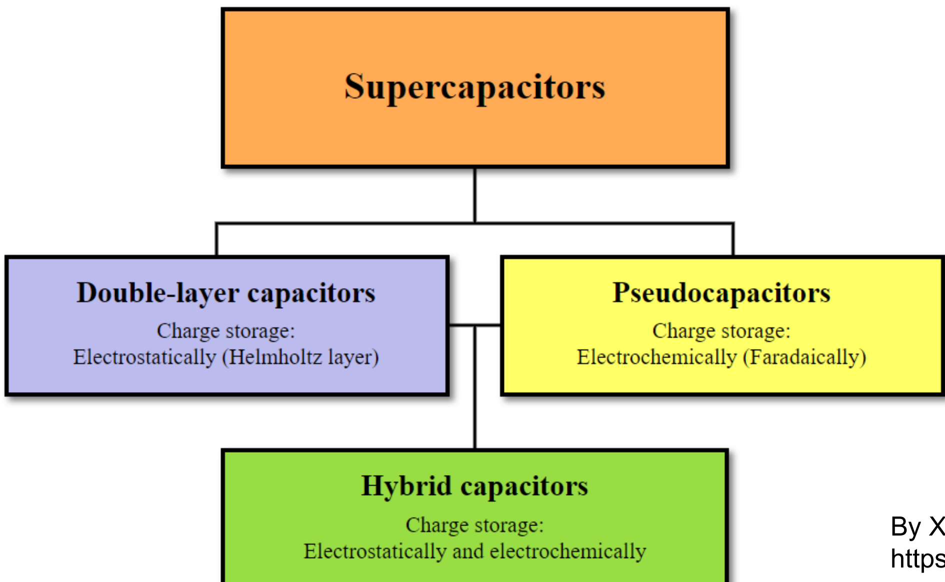
SC

- High-capacity capacitor with a capacitance value much higher than other capacitors, but with lower voltage limits
- Bridges the gap between electrolytic capacitors and rechargeable batteries
- Stores 10-100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerates many more charge and discharge cycles than rechargeable batteries
- SC are used in applications requiring many rapid charge/discharge cycles, rather than long term compact energy storage — in automobiles, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage, or burst-mode power delivery. Smaller units are used as power backup for static random-access memory (SRAM)

Supercapacitors (cont'd)

- Unlike ordinary capacitors, supercapacitors do not use the conventional solid dielectric, but rather, they use electrostatic double-layer capacitance and electrochemical pseudocapacitance, both of which contribute to the total capacitance of the capacitor, with a few differences:





By Xoneca - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=34203771

Performance parameters of Supercapacitors
compared with electrolytic capacitors and lithium-ion batteries

Parameter	Aluminium electrolytic capacitors	— Supercapacitors —			Lithium-ion batteries
		Double-layer capacitors (memory backup)	Pseudocapacitors	Hybrid (Li-Ion)	
Temperature range, Celsius (°C)	−40 ··· +125 °C	−40 ··· +70 °C	−20 ··· +70 °C	−20 ··· +70 °C	−20 ··· +60 °C
Maximum charge, Volts (V)	4 ··· 630 V	1.2 ··· 3.3 V	2.2 ··· 3.3 V	2.2 ··· 3.8 V	2.5 ··· 4.2 V
Recharge cycles, thousands (k)	< unlimited	100 k ··· 1 000 k	100 k ··· 1 000 k	20 k ··· 100 k	0.5 k ··· 10 k
Capacitance, Farads (F)	≤ 2.7 F	0.1 ··· 470 F	100 ··· 12 000 F	300 ··· 3 300 F	—
Specific energy, Watt hours per kilogram (Wh/kg)	0.01 ··· 0.3 Wh/kg	1.5 ··· 3.9 Wh/kg	4 ··· 9 Wh/kg	10 ··· 15 Wh/kg	100 ··· 265 Wh/kg
Specific power, Watts per gram (W/g)	> 100 W/g	2 ··· 10 W/g	3 ··· 10 W/g	3 ··· 14 W/g	0.3 ··· 1.5 W/g
Self-discharge time at room temp.	short (days)	middle (weeks)	middle (weeks)	long (month)	long (month)
Efficiency (%)	99%	95%	95%	90%	90%
Working life at room temp., in years (y)	> 20 y	5 ··· 10 y	5 ··· 10 y	5 ··· 10 y	3 ··· 5 y

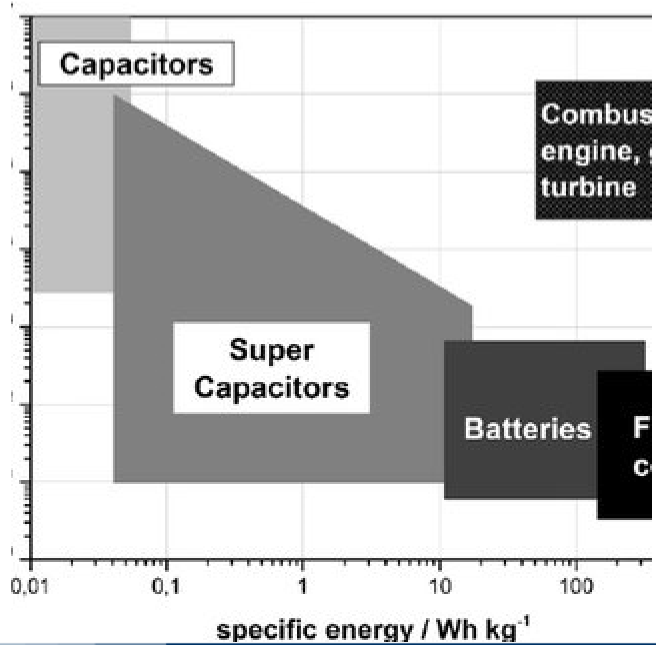
Supercapacitors-Capacitors-Batteries

Electrolytic capacitors

- feature nearly unlimited charge/discharge cycles, high dielectric strength (up to 550 V) and good frequency response as alternating current (AC) reactance in the lower frequency range. Supercapacitors can store 10 to 100 times more energy than electrolytic capacitors, but they do not support AC applications

With regards to rechargeable batteries

- supercapacitors feature higher peak currents, low cost per cycle, no danger of overcharging, good reversibility, non-corrosive electrolyte and low material toxicity. Batteries offer lower purchase cost and stable voltage under discharge, but require complex electronic control and switching equipment, with consequent energy loss and spark hazard given a short



Protection circuit

For Li-xx batteries

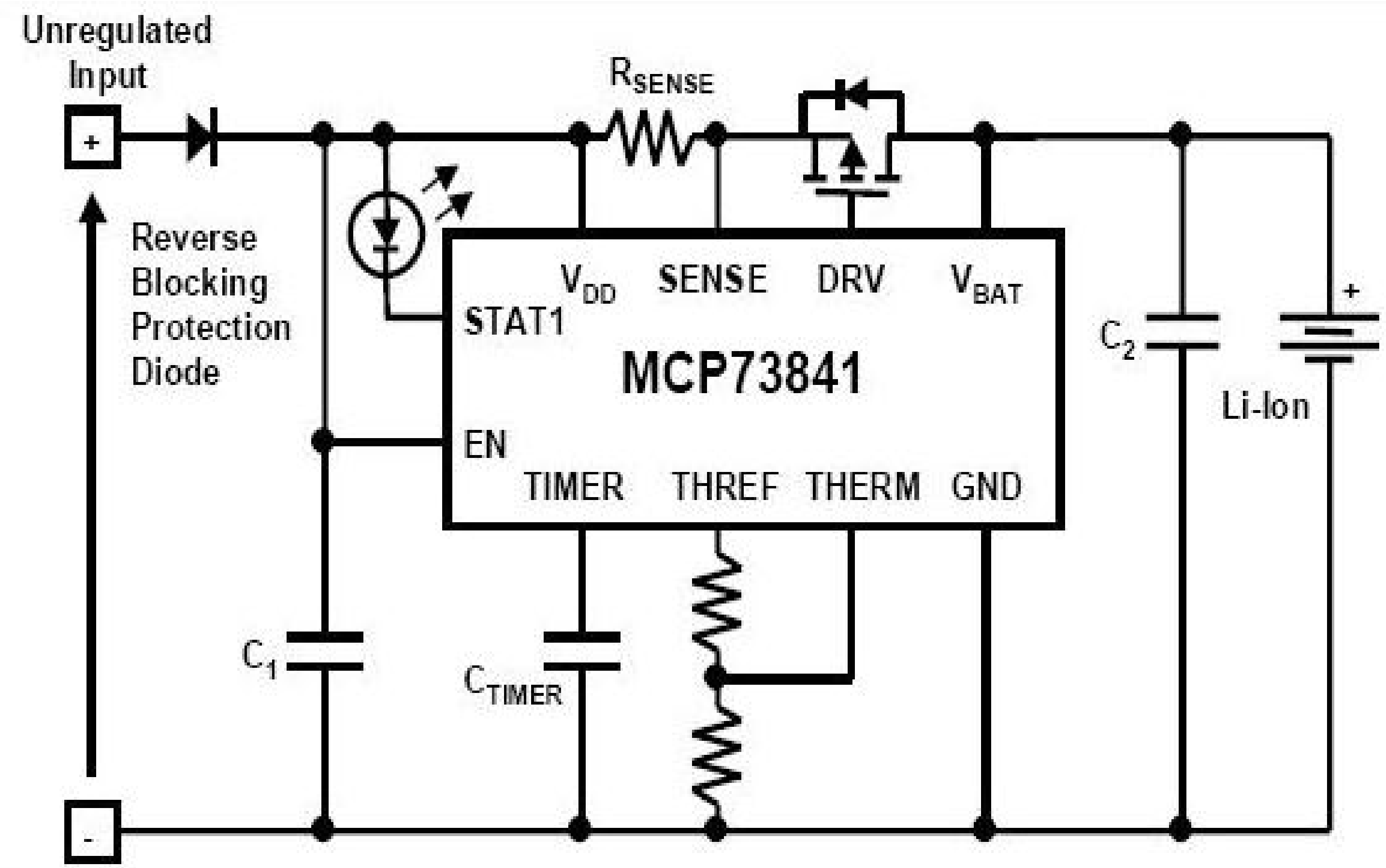
Protects the battery in case of

- Short-circuit on power supply
- Complete discharge
- High voltage during charge phase
- High temperature

Like every circuit it occupies space and drains energy

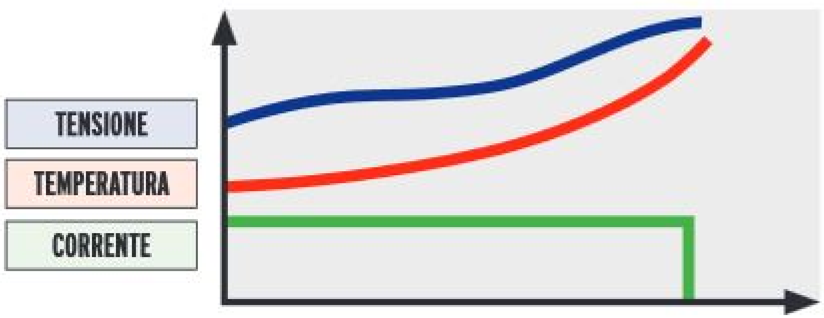
Protection circuit

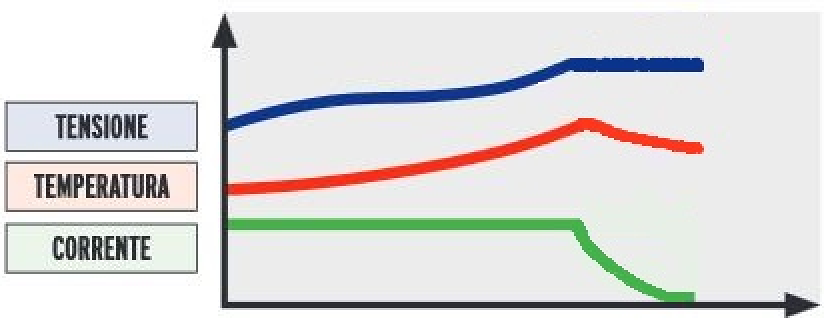
Example

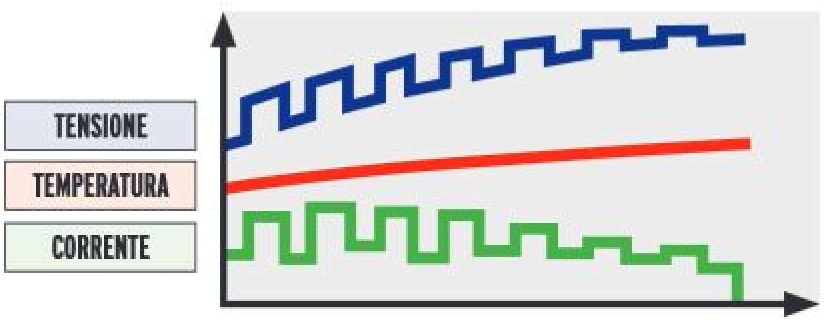


Protection circuit

Determines the charge rate to reduce battery wear





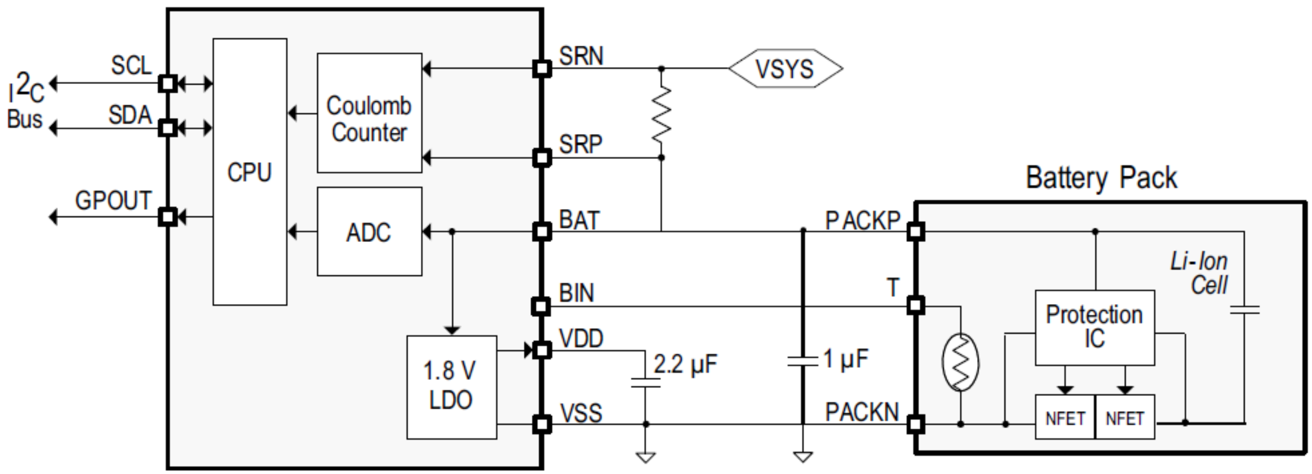


Battery fuel gauge exists as ICs

E.g. from the Texas Instrument bq27220 data sheet

- bq27220 battery fuel gauge is a single-cell gauge that requires minimal user configuration and system microcontroller firmware development
- It uses the Compensated End-of-Discharge Voltage (CEDV) algorithm for fuel gauging, and provides information such as remaining battery capacity (mAh), state-of-charge (%), runtime-to-empty (min), battery voltage (mV), temperature (°C), and state-of-health (%)
- The bq27220 battery fuel gauge has ultra-low power consumption in NORMAL (50 µA) and SLEEP (9 µA) modes, leading to longer battery runtime
- Configurable interrupts help save system power and free up the host from continuous polling. Accurate temperature sensing is supported via an external thermistor

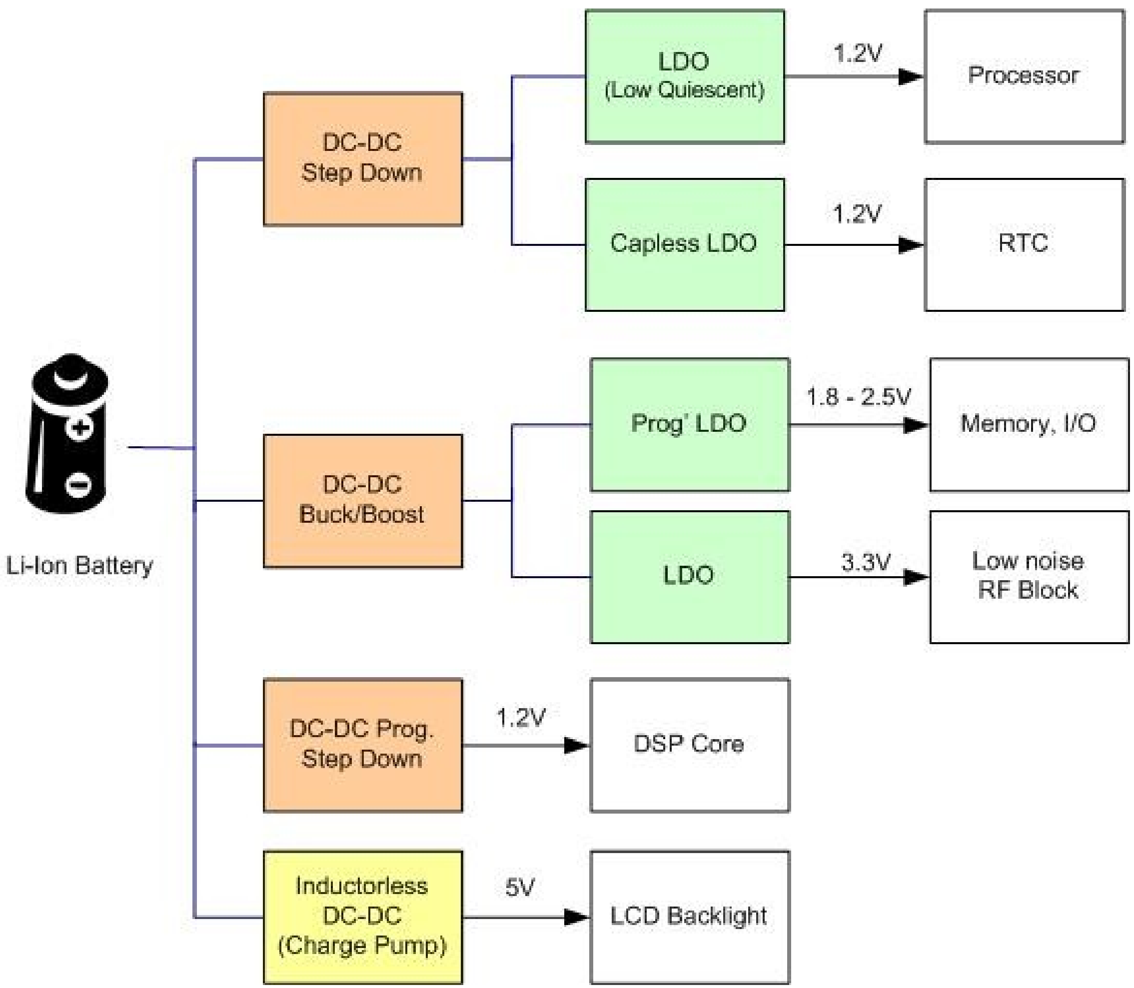
Simplified Schematic (System-Side)



Power Management

- **Mixed circuits (analog and digitals) needs different PDN (Power Distribution Network)**
  - Different power supplies
- **A single system may need different voltage to power each of its blocks**
- **The ability to modulate the power supply voltage allows power-saving techniques**
  - Dynamic power can be reduced in digital circuits by lowering voltage when the system is idle, or there is no need of computing power

Typical Portable System Power Management



DC-DC Converters

- **Linear LDO**
  - Output voltage is regulated with an internal loop

- **Switching (buck-boost, boost, buck)**
  - The conversion is done with an inductor which stores magnetic energy for a given time, the energy is then transferred to the load as a controlled voltage

LDO

(Vout<Vin)

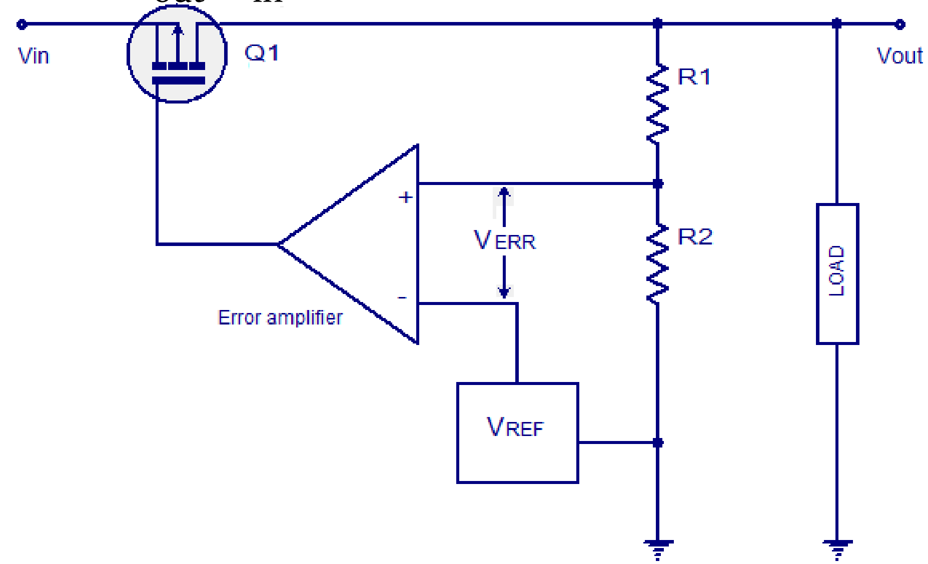
- **Low Drop-Out regulator**
- **Optimal if Vout is a bit lower then Vin**
- **Used for medium/low power applications**
- **Clean Vout**
- **Vout can be changed by varying Vref**
- **Low sensibility on the output currents for frequencies where opamp gain is high (dozens of kHz)**

$$V_{OUT}\frac{R_2}{R_1+R_2}=V_{REF}\rightarrow V_{OUT}=V_{REF}\frac{R_1+R_2}{R_2}$$

$$\eta=P_{out}/P_{in}$$

$$\Rightarrow \quad \eta\approx V_{out}/V_{in}$$

$$I_{out}\approx I_{in}$$



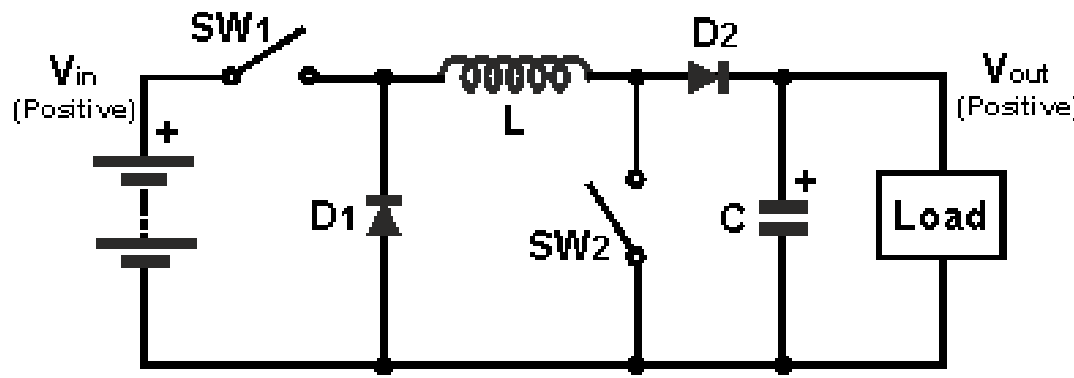
LDO voltage regulator schematic

www.circuitstoday.com

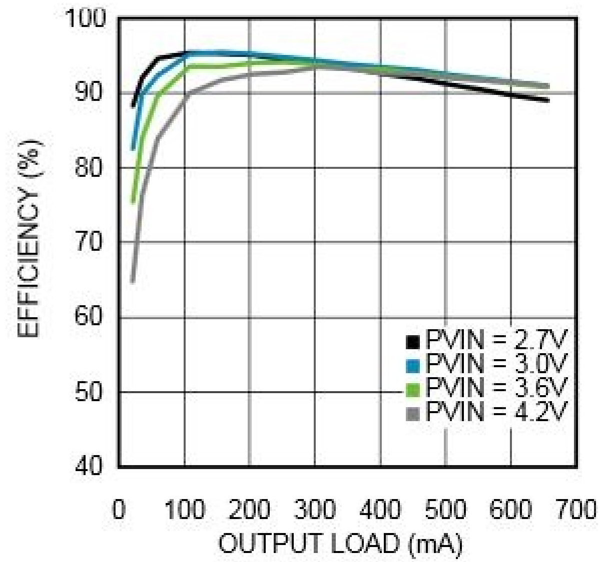
DC/DC buck-boost

Vout>Vin; Vout<Vin

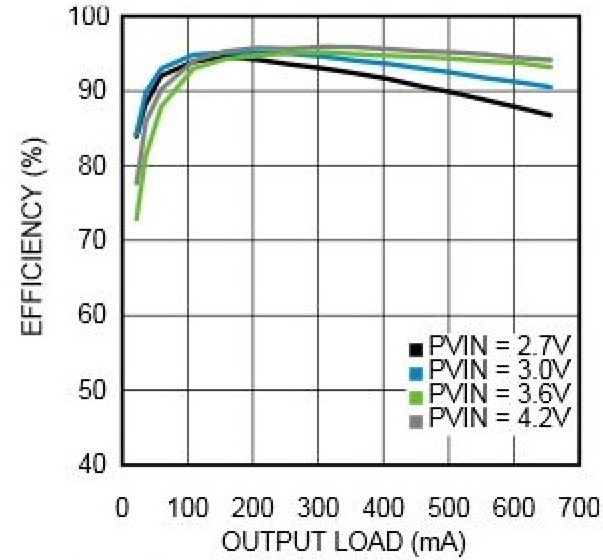
- **Output can be higher or lower then input depending on the application**



- **Efficiency is almost constant and depends on the difference between input and output (90%-95%)**

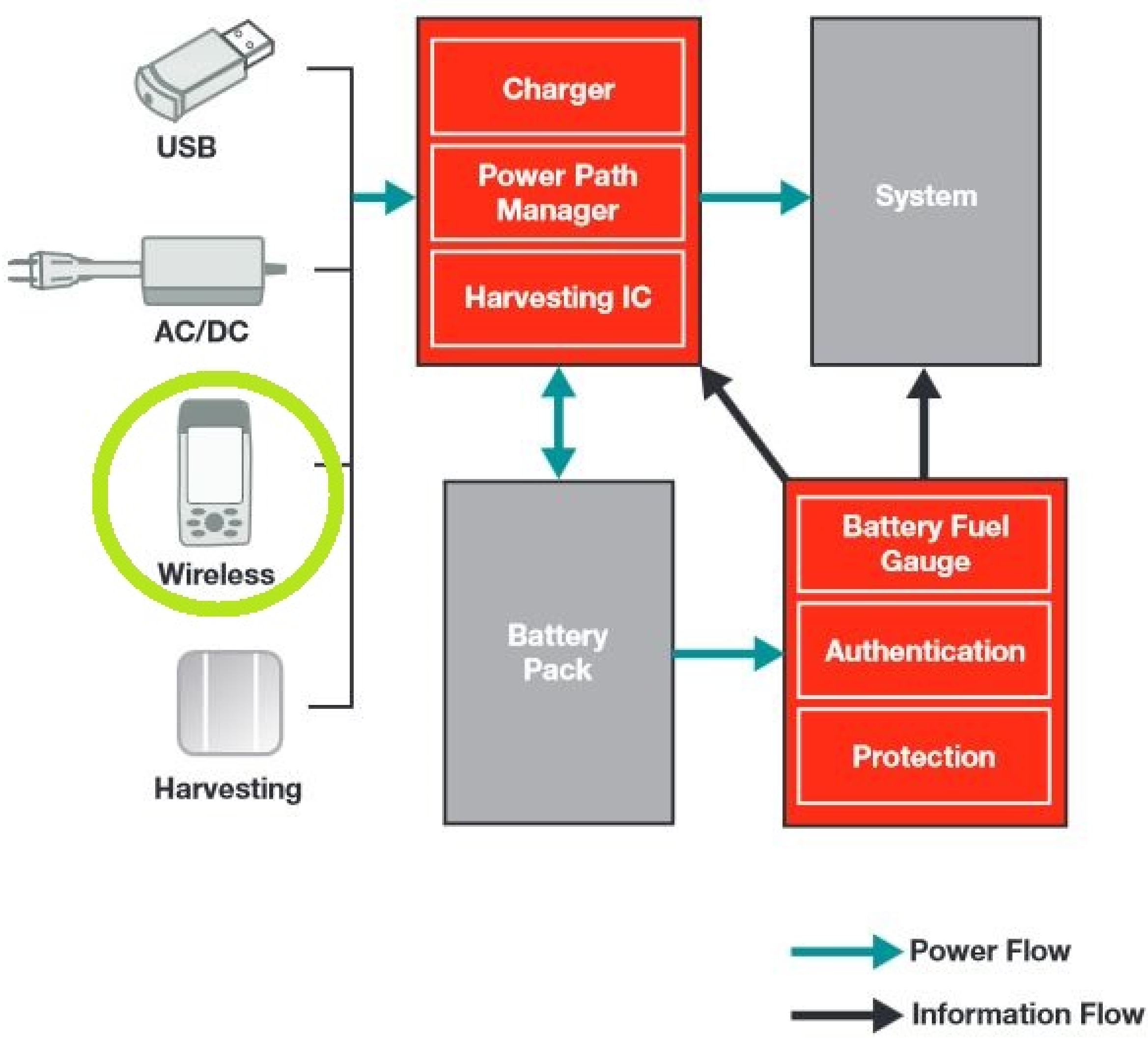


V_{OUT} = 2.4 V



V_{OUT} = 3.6 V

Portable Power System Diagram



Wireless Charging

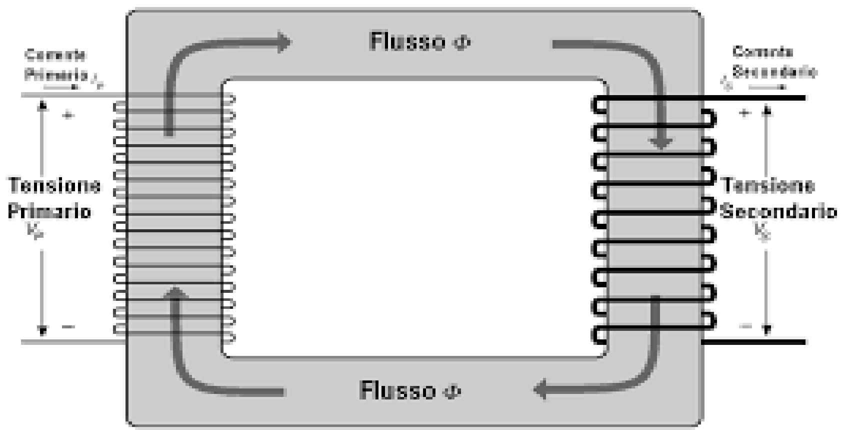
- **Magnetic induction is the most common wireless energy transfer method**

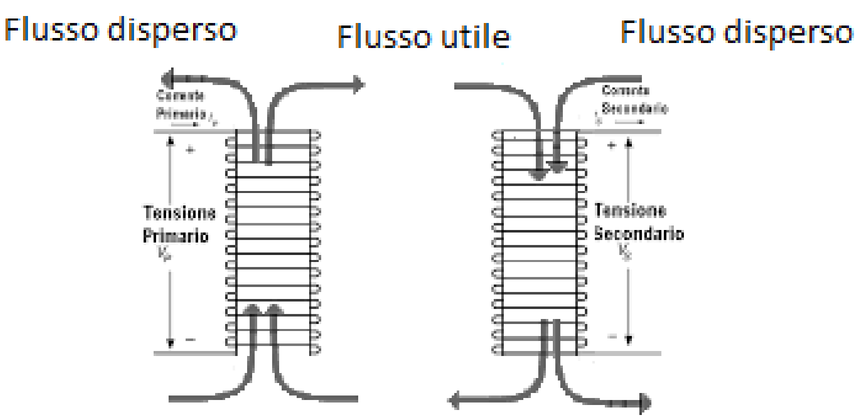
- **An alternative to this method is the use of electromagnetic radiations (microwaves) which can guarantee higher distances between charger and devices**

Magnetic Induction Method

- Growing number of wireless charge enabled devices
- Wireless transmitter can be integrated into commonly used objects

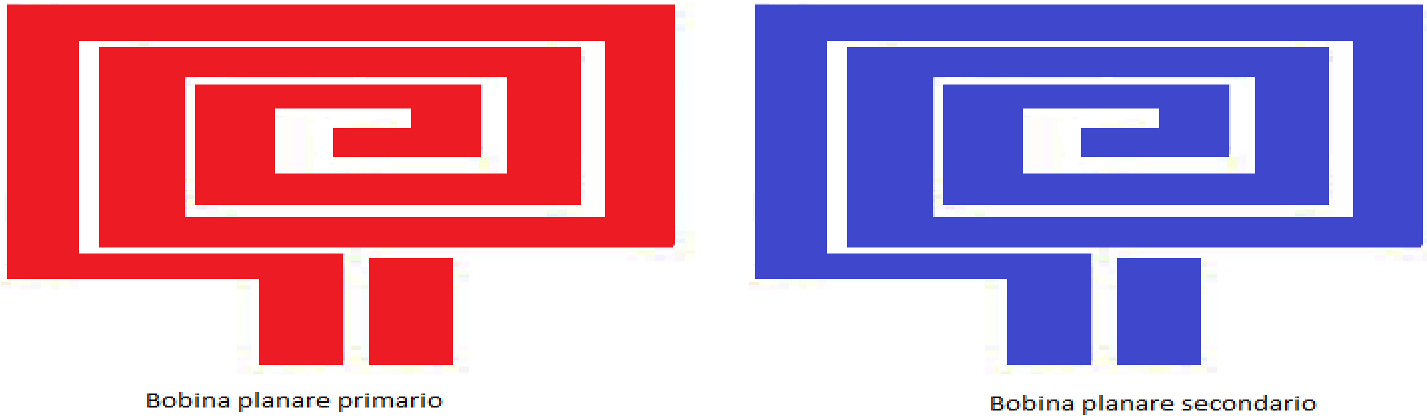
Magnetic Induction Method

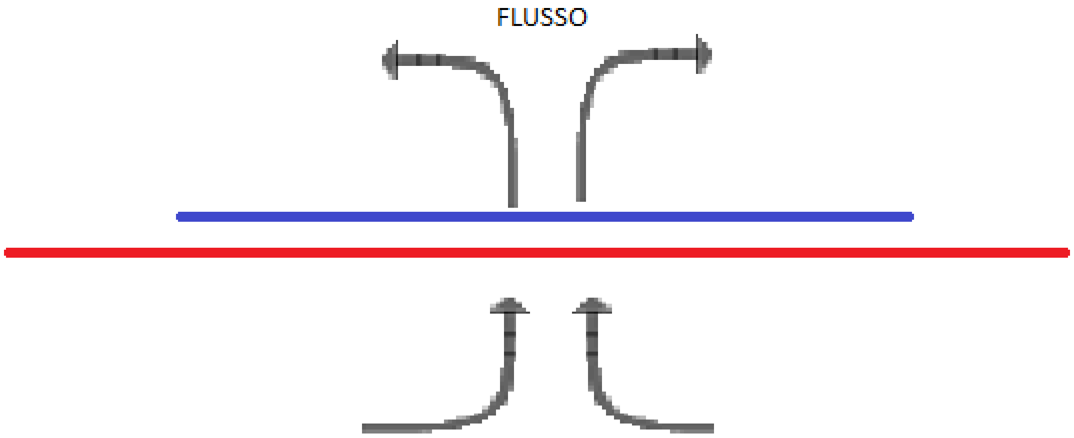




- **Absence of ferromagnetic core causes non-optimal coupling between the two circuits due to dispersed flow**

Magnetic Induction Method





Planar coils are easy to embed into compact devices

Magnetic Induction Method

- **Inductor merit factor** $Q = \frac{\omega L}{R} = 2\pi \times \frac{\text{Energia immagazzinata}}{\text{Energia dissipata per ciclo}}$

- **Efficiency lowers when**
  - with distance (z/D > 1)
  - coils diameters are too different (D2 / D <0.3)
- **Good efficiency (> 90%) when**
  - low distance (z / D <0.1)
  - coils have similar dimensions (D2 / D = 0.5..1)

$\omega \uparrow \rightarrow Q \uparrow$

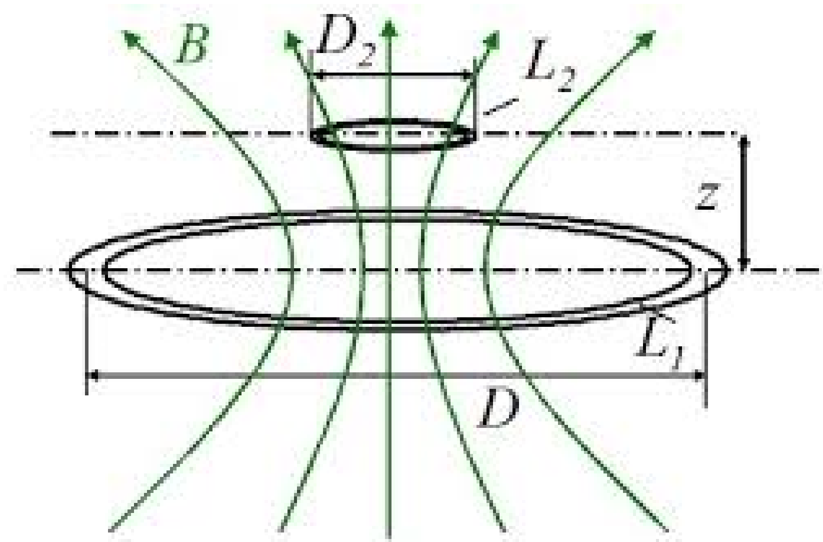
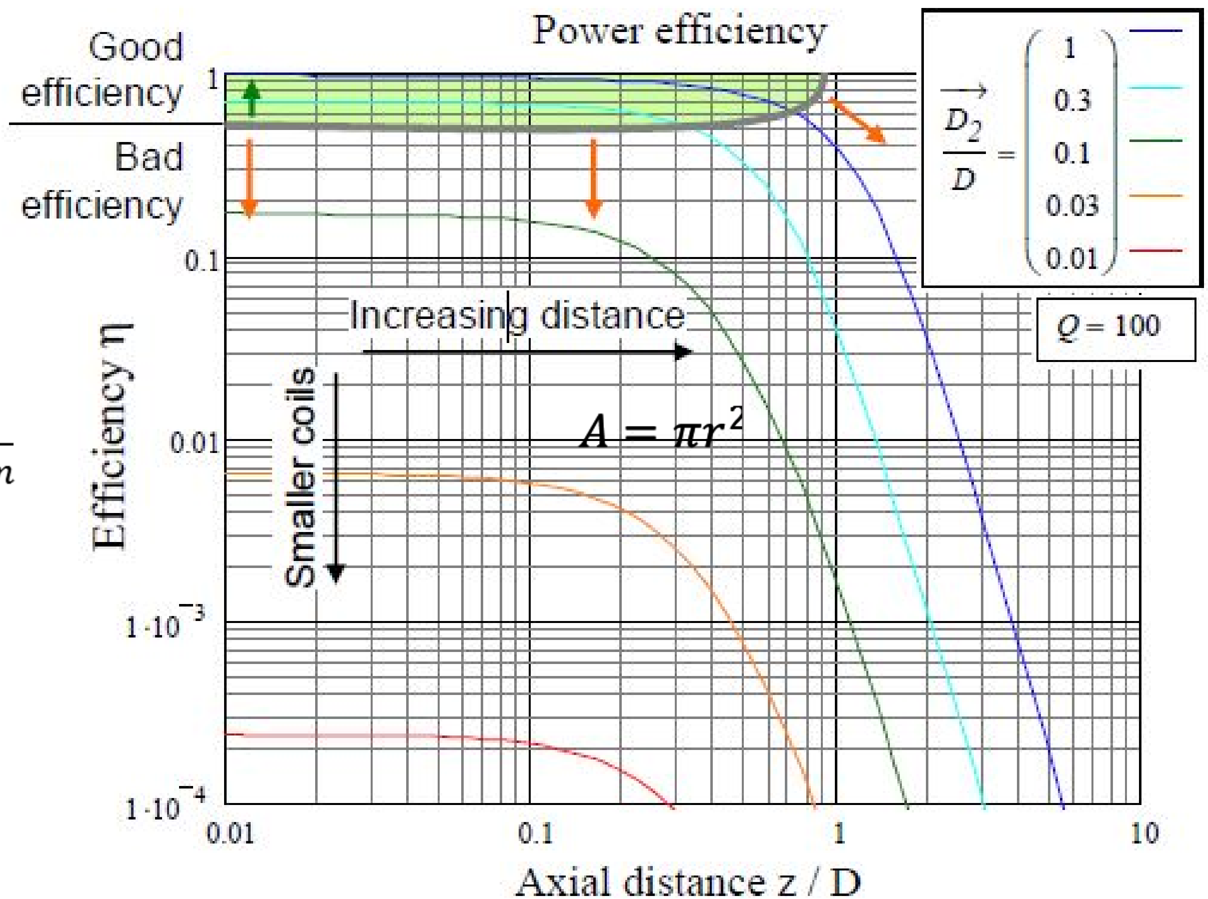


Figure 1 Typical arrangement of an inductively coupled power transfer system

- **Functions relatives to coils with merit factor of Q = 100**

$$\eta=\frac{Pout\_sec}{Pout\_prim}$$



Qi Standard for wireless charging

- **Interface standard for inductive electrical power transfer, developed by Wireless Power consortium in 2008**

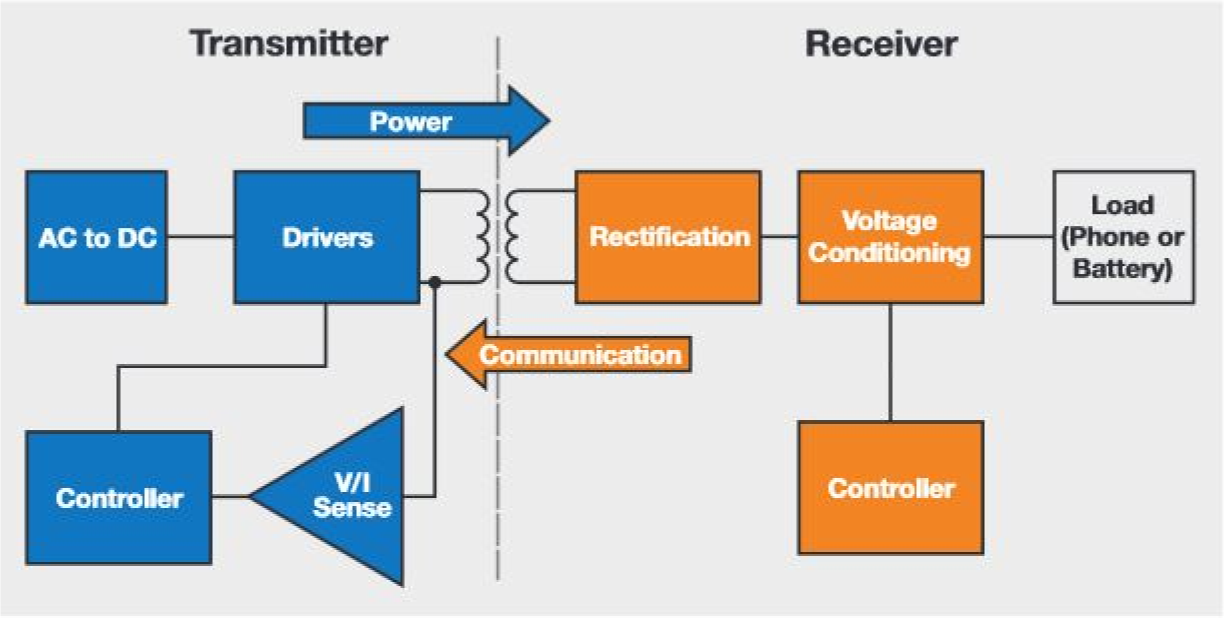
- **WPC encompasses more than 140 members around the world**

Qi Standard for wireless charging

- Maximum distance between the charging base and the device is 4 cm (usually 0.5 cm)
- Inductive energy transfer between two coils
- Up to 5W can be transferred

Qi Standard for wireless charging

- **Qi standard defines 3 key areas of the system**
  - **Transmitter**: element which provides inductive power;
  - **Receiver**: element which uses the energy;
  - **Communication**: uni-directional from receiver to transmitter



Qi - Transmitter

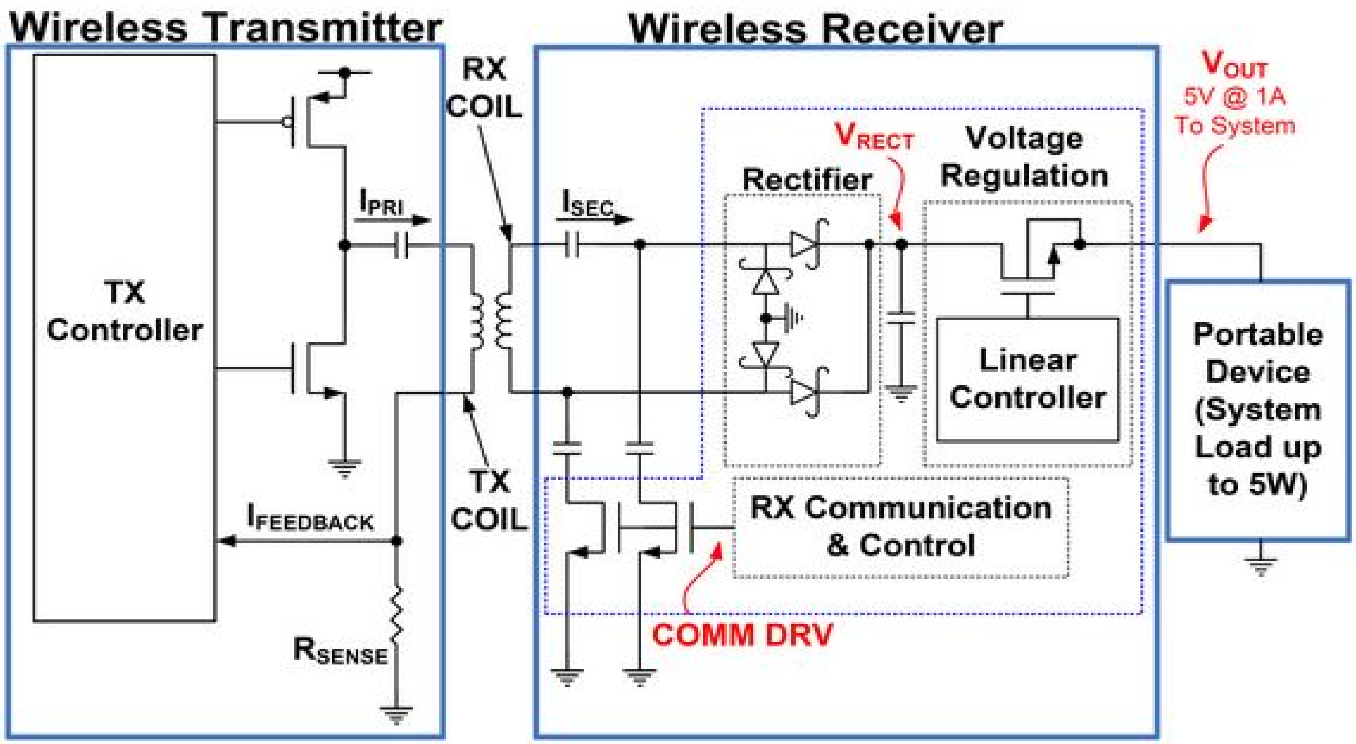
- **The transmitter is composed of:**
  - Coil used for energy transfer;
  - Coil driver, necessary for the communication;
  - Demodulation circuit for primary voltage or current
  - (see communication)

Qi – Receiver, main components

- Coil magnetic coupled with transmitter coil
- AC/DC converter
- Controller which manages the communication

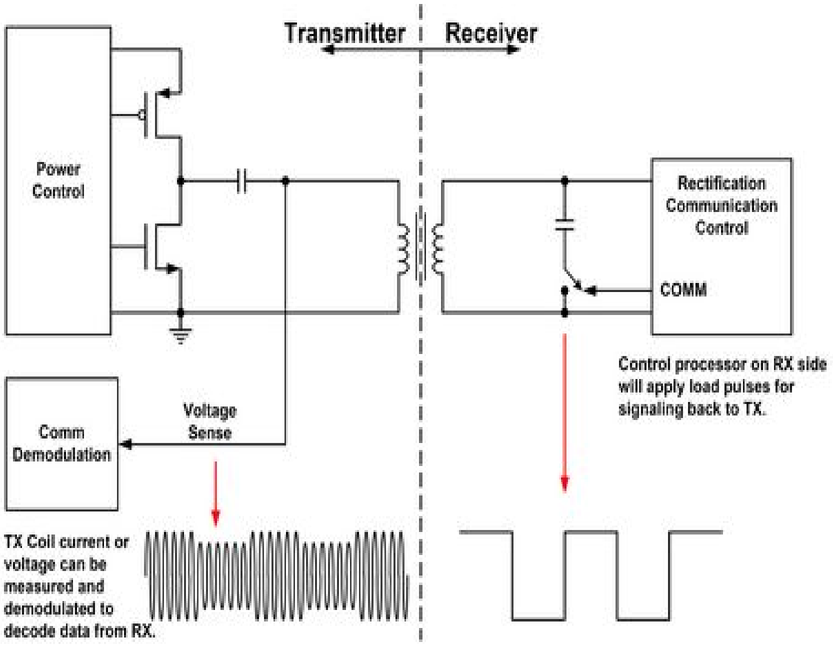
Qi – example of implementation

- **Transmitter: resonant circuit which generates a sinusoidal signal on the coil**
    - Signal freq. is in the rage of 100-200 kHz
- **This signal induces a e.m.f. on the receiver coil used by a rectifier-regulator circuit to power the system**



Qi – Communication

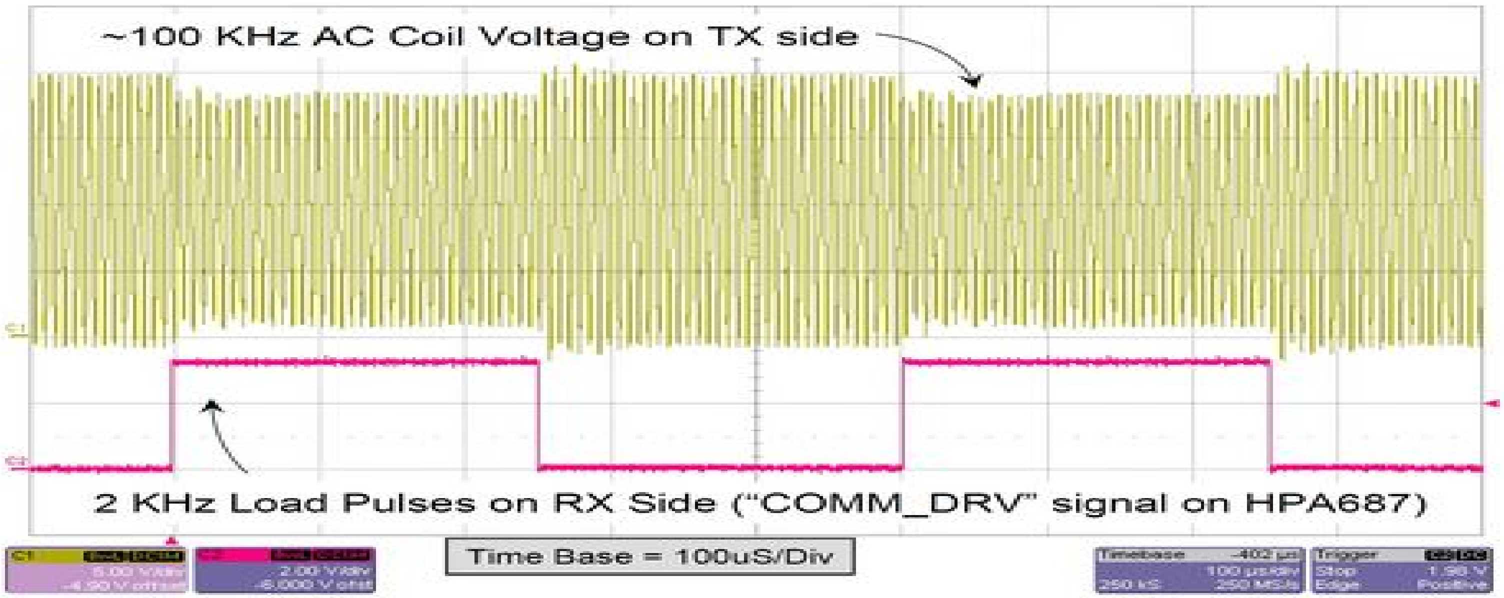
- **Communication between transmitter and receiver is done using load modulation**
  - Impedance variations of the receiver coil causes variations in the output voltage and current at transmitter; the information is associated to those variations
  - Transmission is done without energy dissipation from receiver
  - Switching frequency is in the order of kHz



Qi – Communication: ASK modulation

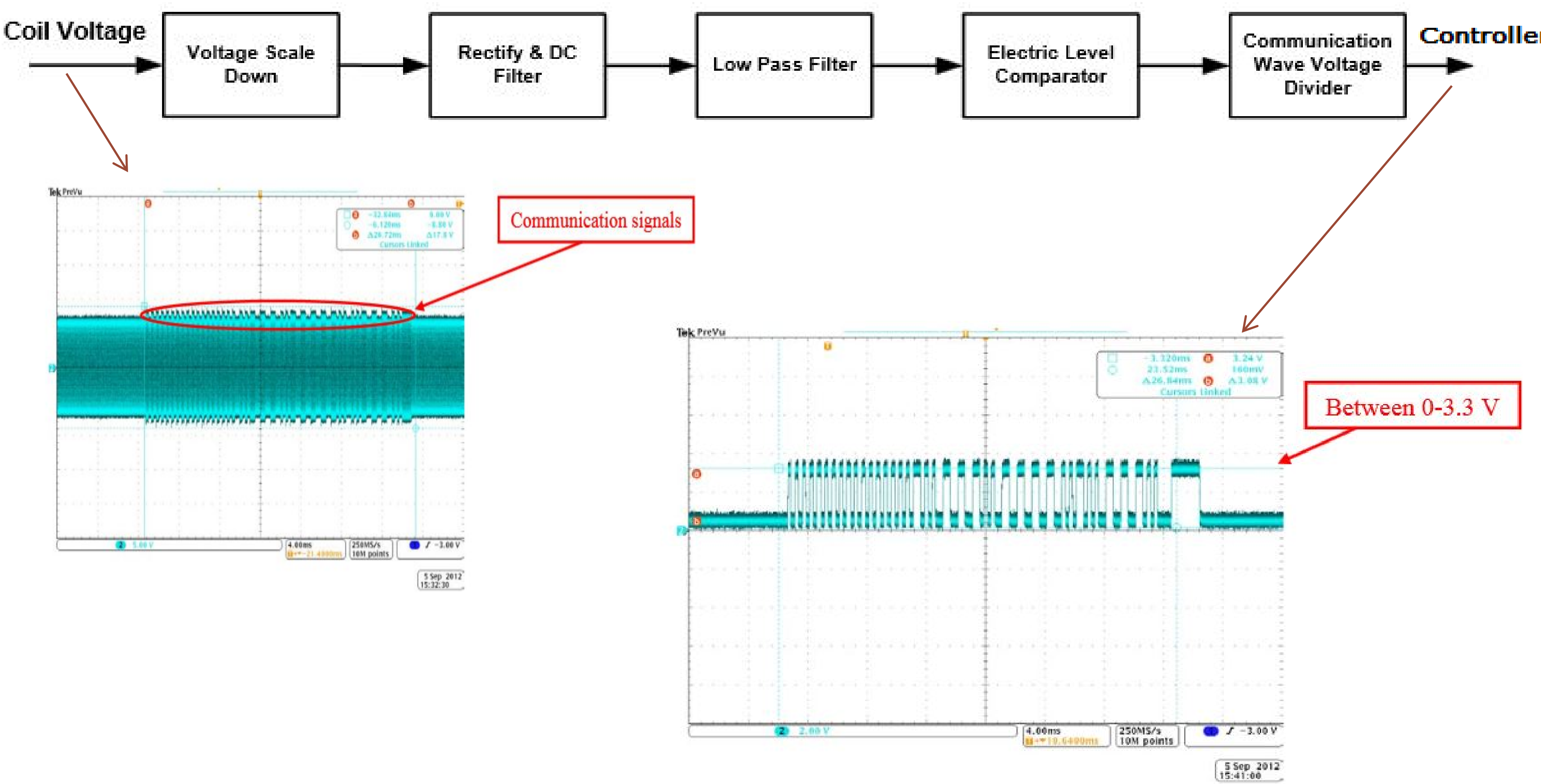
- **Amplitude Shift Keying (ASK) is a relatively simple modulation scheme**
    - ASK is equivalent to the amplitude modulation of the analog signal, and the carrier frequency signal is multiplied by a binary digital.
- **Frequency and phase are kept constant, and the amplitude is variable according the symbol to be transmitted**
- **Information bits are passed through the carrier's amplitude**
- **Called binary amplitude shift keying (2ASK) because signals can take only two binary levels, 0 or 1**

- **Modulation results**



- **Merit factor and transmission efficiency can be increased with higher carrier frequencies**

Qi – Communication



Qi – Protocol

- **Communication phases as described by Qi standard**
  - **Analog ping**
    - transmitter detects the presence of an object
  - **Digital ping**
    - a longer version of the analog ping, gives receiver the time to reply. If the packet is valid transmitter continues to power the coil
  - **Identification and configuration phase**
    - receiver sends necessary information to be identified and to configure the power transmission

Qi – Protocol

- **Power-transfer phase**
  - receiver sends packets to transmitter at regular time intervals (250ms) to increase or decrease power supply;
- **End power transfer**
  - to end power transfer, the receiver sends an “End power” message or sends no communication for 1.25 seconds. The transmitter enters then a low-power state

Qi – Protocol

- **Signal strength**
  - used to align RX unit on the charging pad
- **Control error packet**
  - returns a signed integer value (-128 to +127) that indicates the degree of error between the value of the input voltage seen by the RX and its desired input voltage
- **End power transfer packet;**
- **Rectified power packet**
  - this is an unsigned integer value that communicates the amount of power the RX sees at the output of the rectifier circuit
  - The TX uses this information to determine the overall coupling efficiency as well as to determine when the RX is at its maximum power limit

ST - WBC

- **as WPC, Power Matters Alliance (PMA) is a global industry organization whose mission is to advance a suite of standards and protocols for wireless power transfer**

The STWBC is the digital controller for wireless battery charger (WBC) transmitters (TX) from STMicroelectronics, offering the most flexible and efficient solution for controlling power transfer to a receiver (RX) in WBC-enabled applications such as phones, wearables, and other battery powered devices that use electromagnetic induction for recharging.

As a member of the Qi Wireless Power Consortium and the PMA (Power Matters Alliance), ST ensures full compatibility with these leading wireless charging protocols and holds certification for the Qi 1.1.2 A11 standard.

The STWBC performs all the functions for transmitter control: thanks to the internal 96 MHz clock and supporting both half-bridge and full bridge topologies, it is able to precisely control the amount of transmitted power to match the requirements of the receiving unit in terms of maximizing the efficiency of the power transfer.

ST - WBC

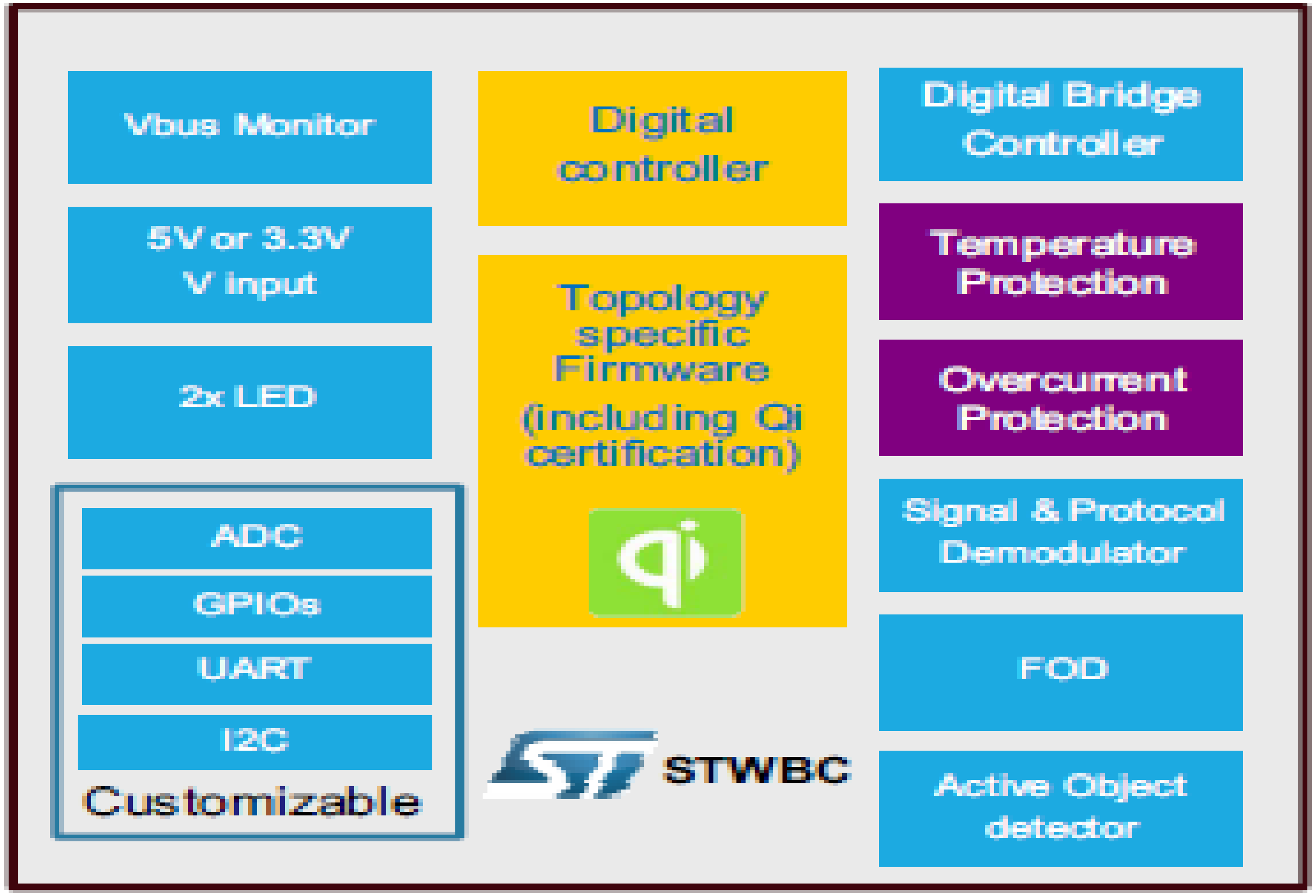
Applications

- Certified Qi A11
  - Evaluation board: STEVAL-ISB027V1
  - Power rate: 5W
  - Input: 5V
- Qi A13[a]
  - Power rate: 5 W
  - Input: 5 - 16 V, 12 V
- Wearable[a]
  - Power rate: 2 W
  - Input: 5 V
- PMA[a]
  - power rate: 5 W
  - input: 5 V

Features

- Digital controller for wireless battery charger transmitter
- Multiple Qi certified and PMA standard compatible
- Support for up to 5 W applications
  - Mobile
  - Wearable, sports gear, medical
  - Remote controllers
- Native support to half-bridge and full bridge topologies
- 5 V supply voltage
- 2 firmware options
  - Turnkey solution for quick design
  - APIs available for application customization[a]
- Peripherals available via APIs[a]
  - ADC with 10 bit precision and 1 MΩ input impedance
  - UART
  - I^2C master fast/slow speed rate
  - GPIOs

ST – WBC, Device architecture



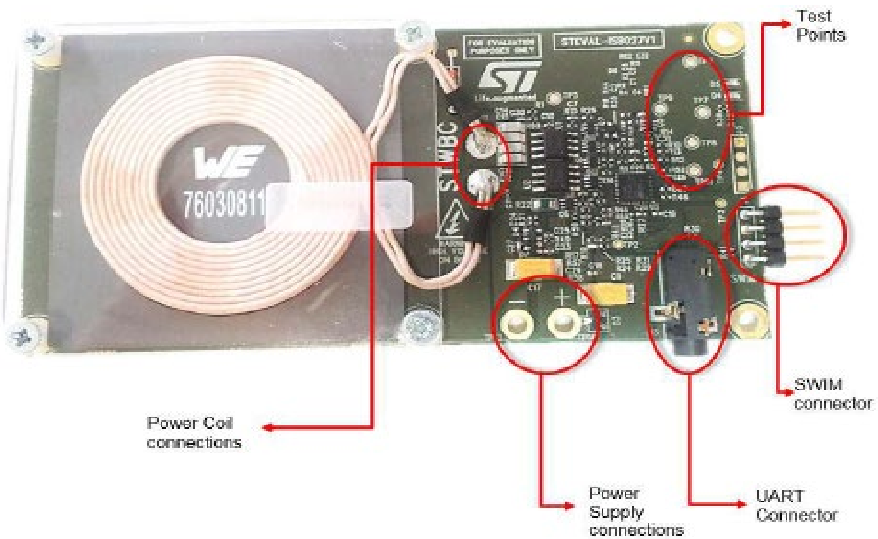
STEVAL-ISB027V1

Description

The STEVAL-ISB027V1 is a Qi 5 Watt wireless battery charger transmitter evaluation board based on the STWBC digital controller for wireless battery charger transmitters. The solution is certified in accordance with the Qi standard, A11 topology. The STEVAL-ISB027V1 provides a complete kit which includes the STWBC IC, firmware, layout and tools. The layout is based on a cost-effective 2-layer PCB.

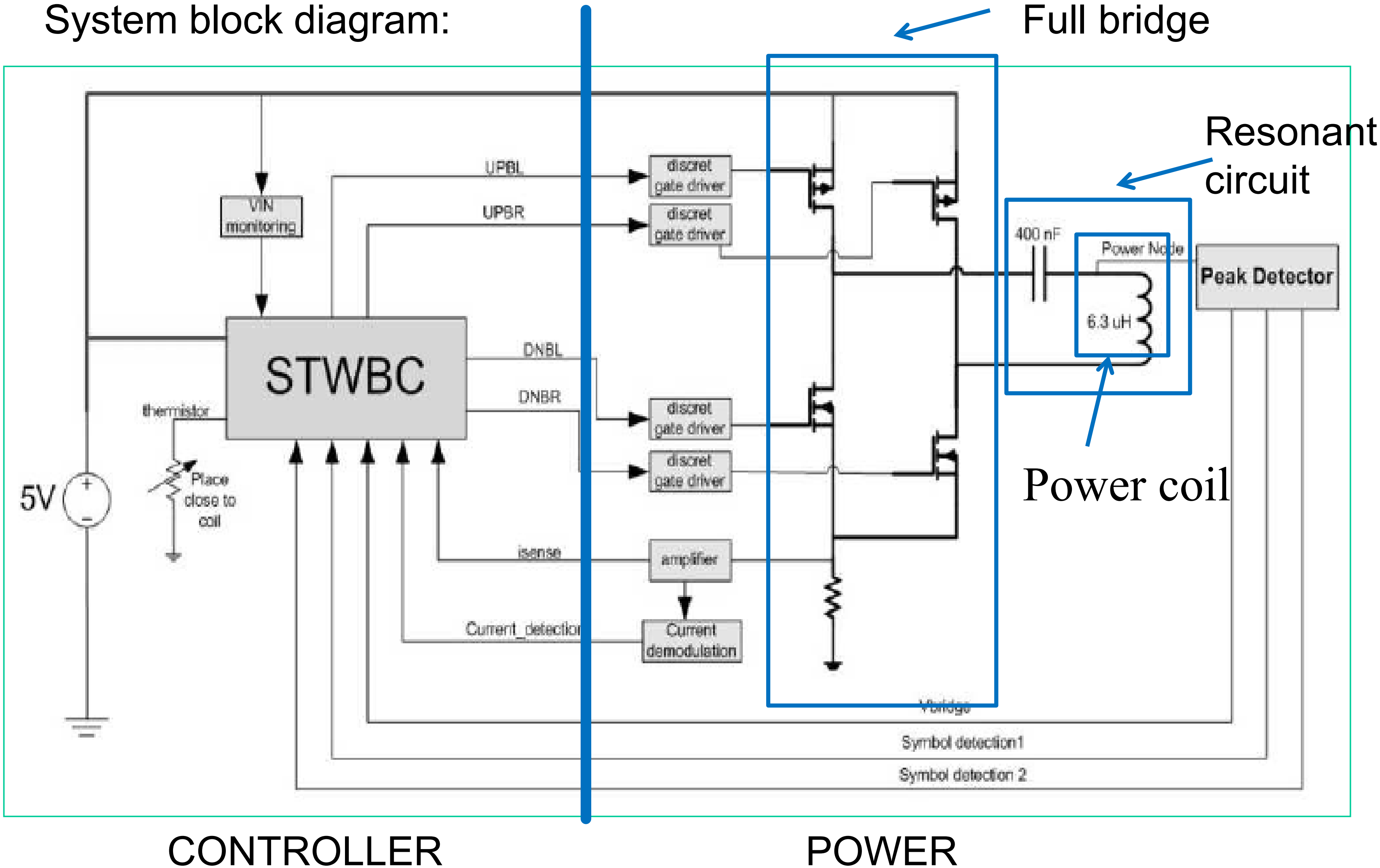
The STEVAL-ISB027V1 board has the following features:

- WPC Qi 1.1.2 certified
- Standard Qi A11-type transmitter and coil
- Resistive and capacitive modulation
- Foreign object detection (FOD)
- LEDs for charge status indication
- UART connection for user interface
- SWIM connection for firmware download
- 5 V power supply



STEVAL-ISB027V1

System block diagram:



References

Batteries:

- https://en.wikipedia.org/wiki/Nickel%E2%80%93cadmium_battery
- https://en.wikipedia.org/wiki/Lithium-ion_battery
- https://en.wikipedia.org/wiki/Lithium_polymer_battery
- http://www.microst.it/Tutorial/carica_ionilitio.htm

Power management:

- http://www.eetimes.com/document.asp?doc_id=1273088&page_number=1
- http://corsiadistanza.polito.it/on-line/Elettronica_di_Potenza_v2/lezionee3/lezione.pdf
- http://www.ti.com/lit/ds/snvs793d/snvs793d.pdf
- http://www.ti.com/lit/sg/slyt420c/slyt420c.pdf

Wireless charging / Qi standard:

- http://cache.freescale.com/files/microcontrollers/doc/app_note/AN4701.pdf
- http://www.low-powerdesign.com/article_TI-Qi.html
- http://www.qiwireless.com
- http://www.ti.com/lit/an/slyt401/slyt401.pdf
- http://www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/DM00152958.pdf
- http://www.st.com/st-web-ui/static/active/en/resource/technical/document/user_manual/DM00158917.pdf