Recent Developments on Supercapacitors and their Applications

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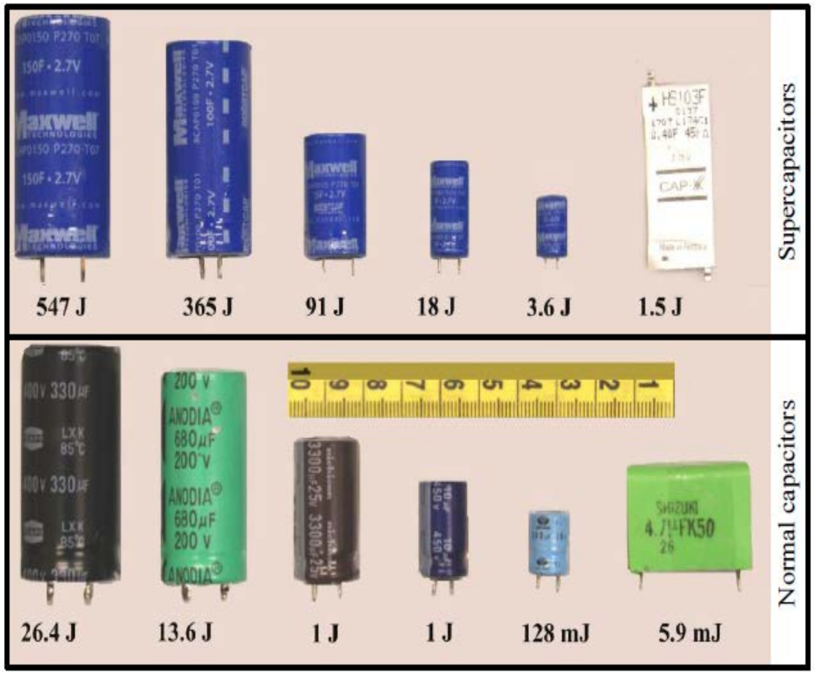
What is a supercapacitor

- Supercapacitor is almost one million times larger in capacitance compared to an electrolytic capacitor
- Its energy storage capacity one to three order larger than an electrolytic
- With a much lower ESR it can provide very high power outputs for short periods of time (high power density)



Comparison of supercapacitor and normal capacitor sizes and maximum energy storage

Supercapacitors versus batteries

Ragone Plot

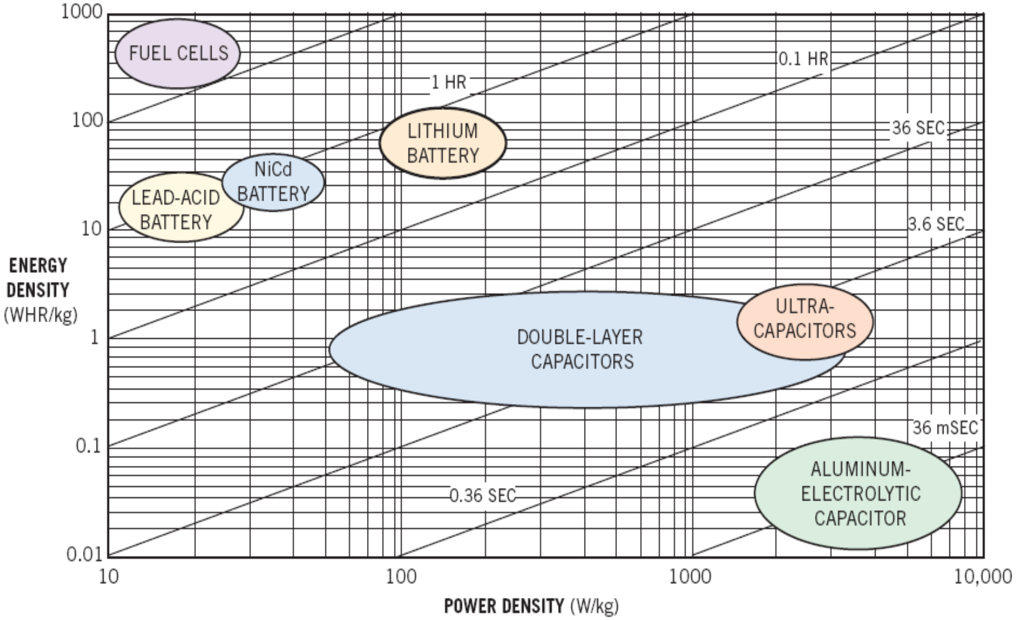


Figure 1 Graphing energy density against power density, conventional batteries occupy the top-left position, and conventional aluminum-electrolytic capacitors occupy the bottom-right. Supercapacitors bridge the space between. Diagonal lines are lines of equal discharge time into a specified load (courtesy Maxwell Technologies).

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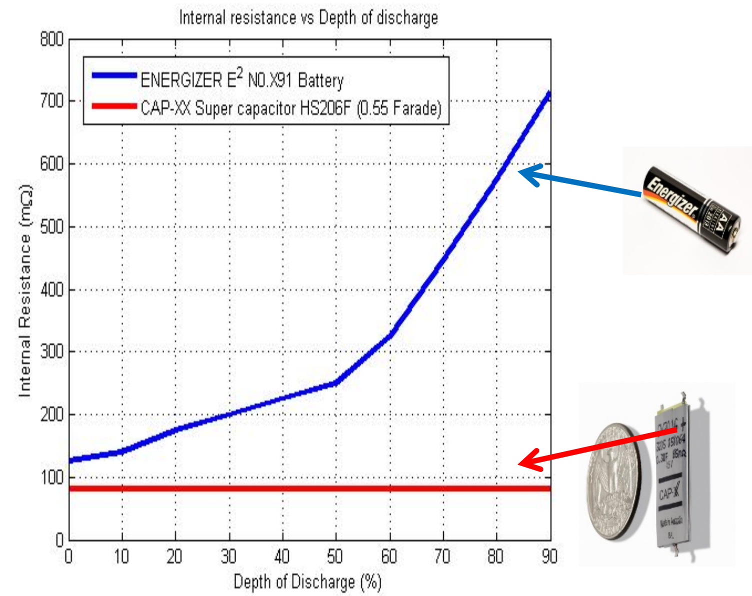
Internal resistance with depth of discharge



SCs with constant and very low ESR can deliver much higher power into a load than an electrochemical battery, where ESR keeps increasing with the discharge.

SCs versus electrolytics- Comparison of Specifications

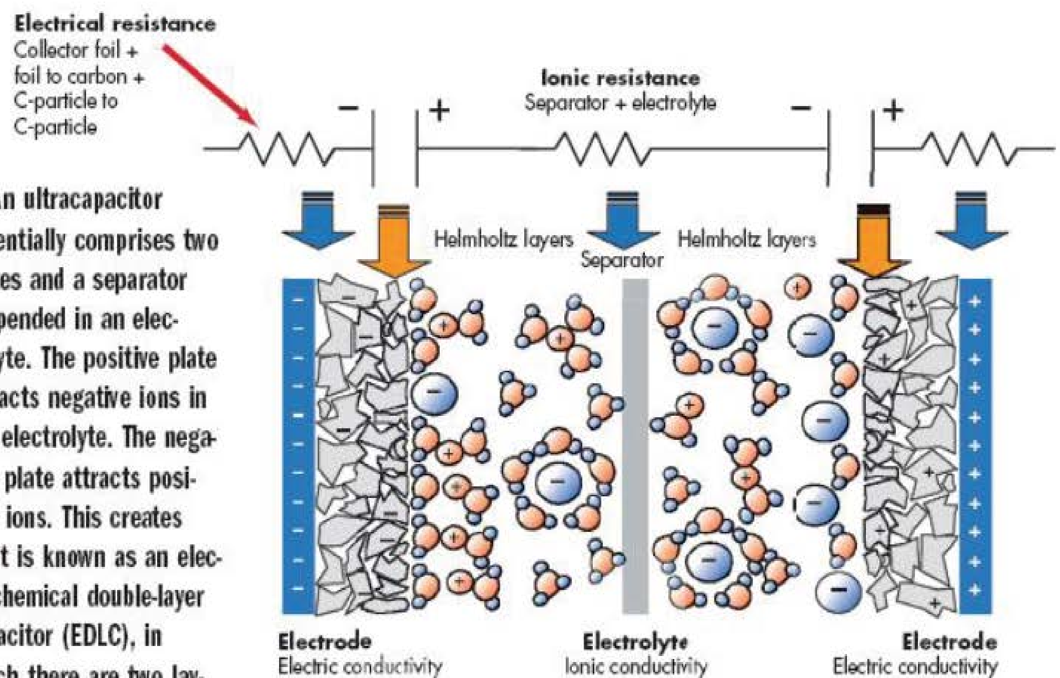
TABLE 2. COMPARISON OF TYPICAL ELECTROLYTIC CAPACITORS AND SUPERCAPACITORS FOR THEIR ESR VALUES AND OTHER USEFUL SPECIFICATIONS

ENERGY STORAGE LIMIT	CAPACITOR TYPE	MANUFACTURER	PARAMETERS			
			CAPACITANCE (µF/F)	TERMINAL VOLTAGE (V)	SHORT CIRCUIT CURRENT (A)	ESR (m Ω)
Less than 1J	Electrolytic	RSS	2200 µF	16	104	153
1-5 J	Supercap	Maxwell	1 F	2.7	3.85	700
		Cap-xx	2.4 F	2.3	115	20
	Electrolytic	Cornell Dubilier	2200 µF	50	704	71
5-50 J	Supercap	Maxwell	10 F	2.5	14	180
		Cap-xx	1.2 F	4.5	112.5	40
		Nesscap	10 F	2.3	33	70
	Electrolytic	Cornell Dubilier	82,000µF	16	1441	11.1
		VICOR	270 µF	200	325	614
Above 50 J	Supercap	Maxwell	350 F	2.7	840	3.2
		Nesscap	120 F	2.3	144	16

In general, SCs have lower ESR than the electrolytic capacitors, but their DC voltage rating is very low.

SC is an electric double layer device

- Inside a SC two capacitors are formed in series



1. An ultracapacitor essentially comprises two plates and a separator suspended in an electrolyte. The positive plate attracts negative ions in the electrolyte. The negative plate attracts positive ions. This creates what is known as an electrochemical double-layer capacitor (EDLC), in which there are two layers of capacitive storage.

$$E = \frac{1}{2}CV^2 \qquad P = \frac{1}{4R}V^2$$

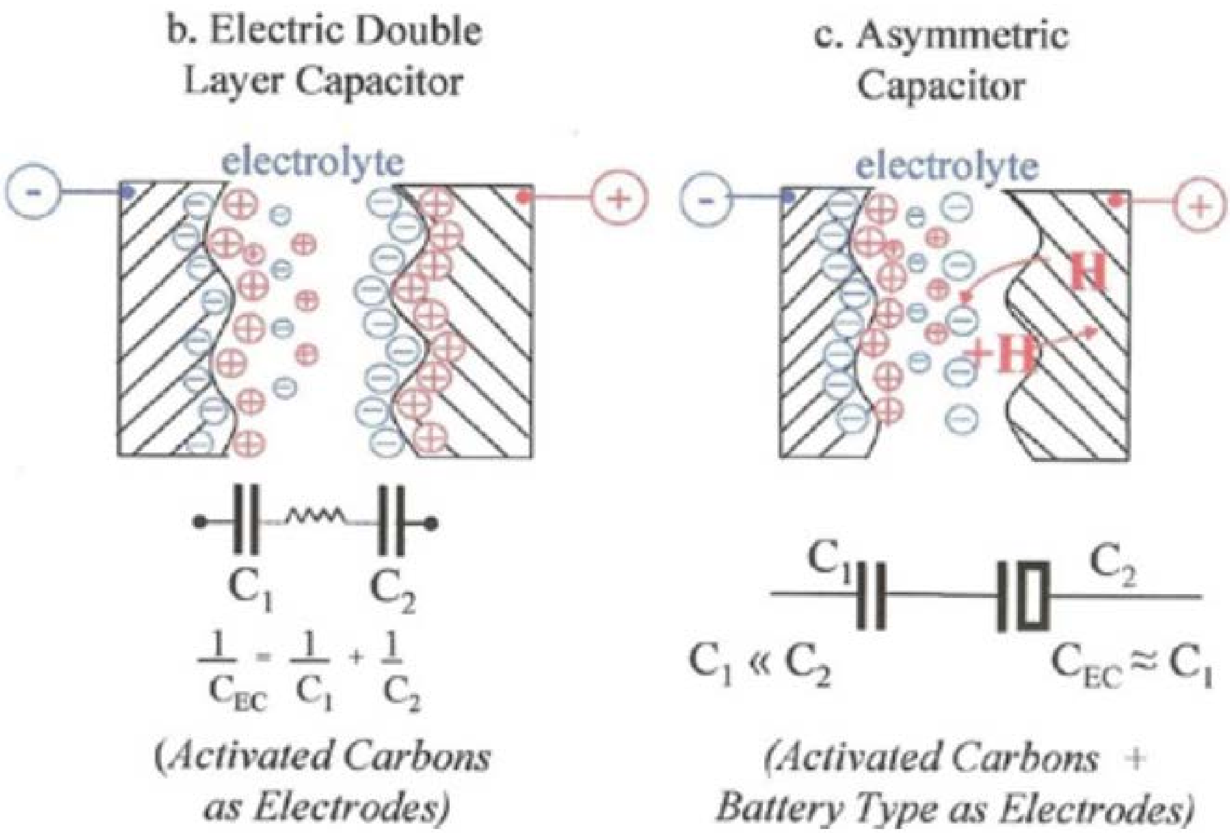
From Traditional Caps to Batteries –With SCs in the middle

Traditional Capacitors	Supercapacitors (symmetrical – usually carbon on a metal electrode on either side)	Hybrid supercapacitors (one supercap electrode + one battery electrode)	Batteries
	Electrochemical Double Layer Capacitors EDLC	Asymmetric Electrochemical Double Layer Capacitors AEDLC	
	Ultracapacitors	When based on a lithium-ion battery – “lithium capacitor” or “Lithium-ion capacitor”	
		When based on a lead acid battery – trade name	

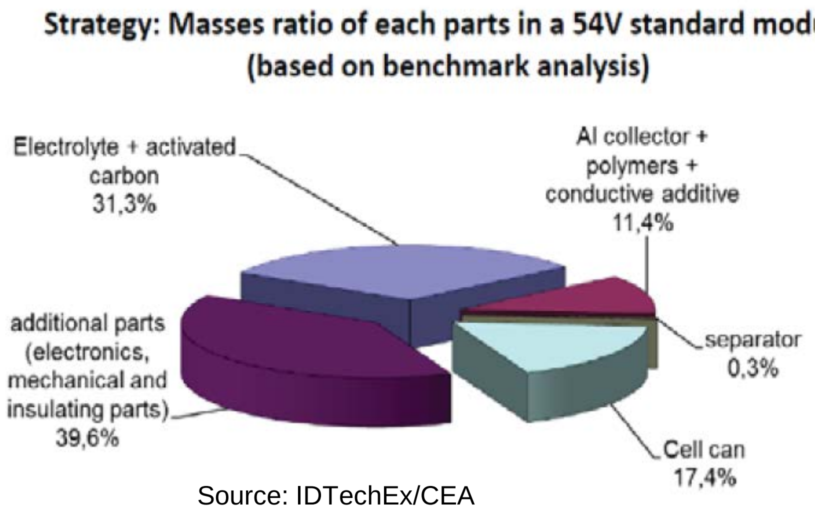
STORES MORE ENERGY Wh/kg or Wh/l →

← *DELIVERS MORE POWER W/kg or W/l*

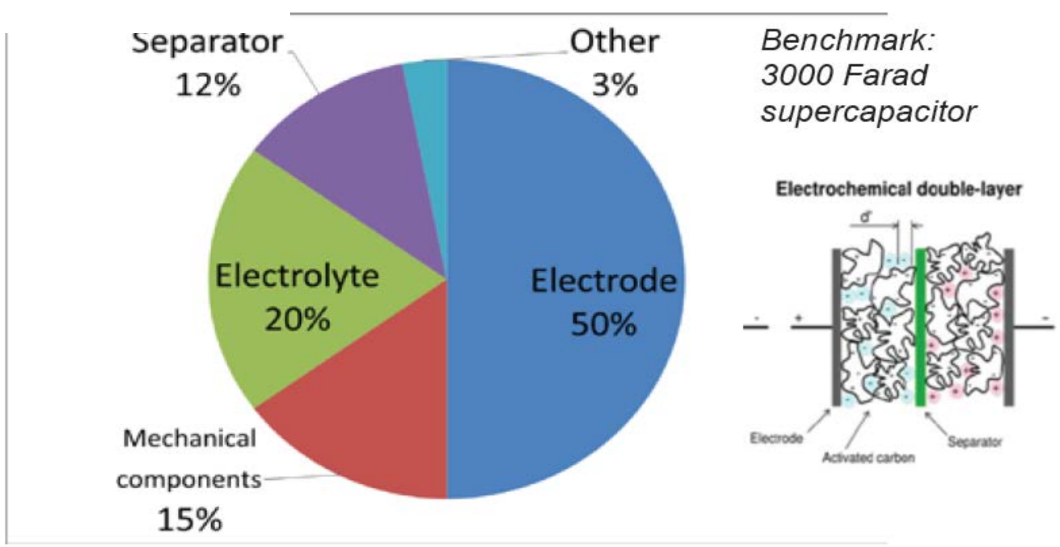
Supercapacitors versus Hybrid Supercapacitors



Internal material and cost structure of (EDLC)



Source: IDTechEx/CEA



Source: IDTechEx, Maxwell Technologies

Electrolytes

	Organic Electrolyte	KOH/H_2SO_4 Aqueous Electrolyte	Aprotic Ionic Liquids (AILs)
Operating voltage	2.7-2.8 V	0.8-1.0 V	~3.0 V
Conductivity	~ 0.02 S/cm	~ 1 S/cm	~ 0.005 S/cm
Maximum Capacitance	150-200 F/g	250-300 F/g	100-120 F/g
Technological, economical and safety aspects	•Manipulation in inert atmosphere •Expensive •Environment Unfriendly	•Easy manipulation •Not Expensive •Environment Friendly	•Performing at high temperature (40-60 C) but decreasing stability •Expensive •Environment friendly

Source IDTechEx

Electrolytes used by the manufacturers –

The percentage represents the number of companies using each type of electrolyte.

Source: IDTechEx

Research trends and commercialisation

- In SCs higher performance is achieved by
  - Increasing electrode surface area
  - Using better electrolytes
- To have larger surface area active research on new materials such as
  - Graphene
  - Graphene oxide
  - Carbon nano-tubes (CNT)

Graphene potential in SC is not fully developed yet but is good enough. Developments on SC manufacturing integration of graphene in progress.

	Specific Surface Area (m2/g)	Conductivity (S/cm)	Specific Capacity (F/g)
Activated Carbon	1000-2000 [4]	600 [7]	90 [5]
Graphene Theoretical	2675 [1]	Higher than 600,000	550 [3]
Graphene Today		649 [2]	147.5-205 [5]
Copper	NA	600000 [6]	NA
Aluminum	NA	350000 [7]	NA

	Lab Level Achievement	Benchmark
Energy	166 F/g - 20 Wh/kg* [8]	4xEnergy AC SC – Equal Pb Acid Bat
Power	75 kW/kg* [8]	one order magnitude higher than AC SC

***Lab Results pack device**

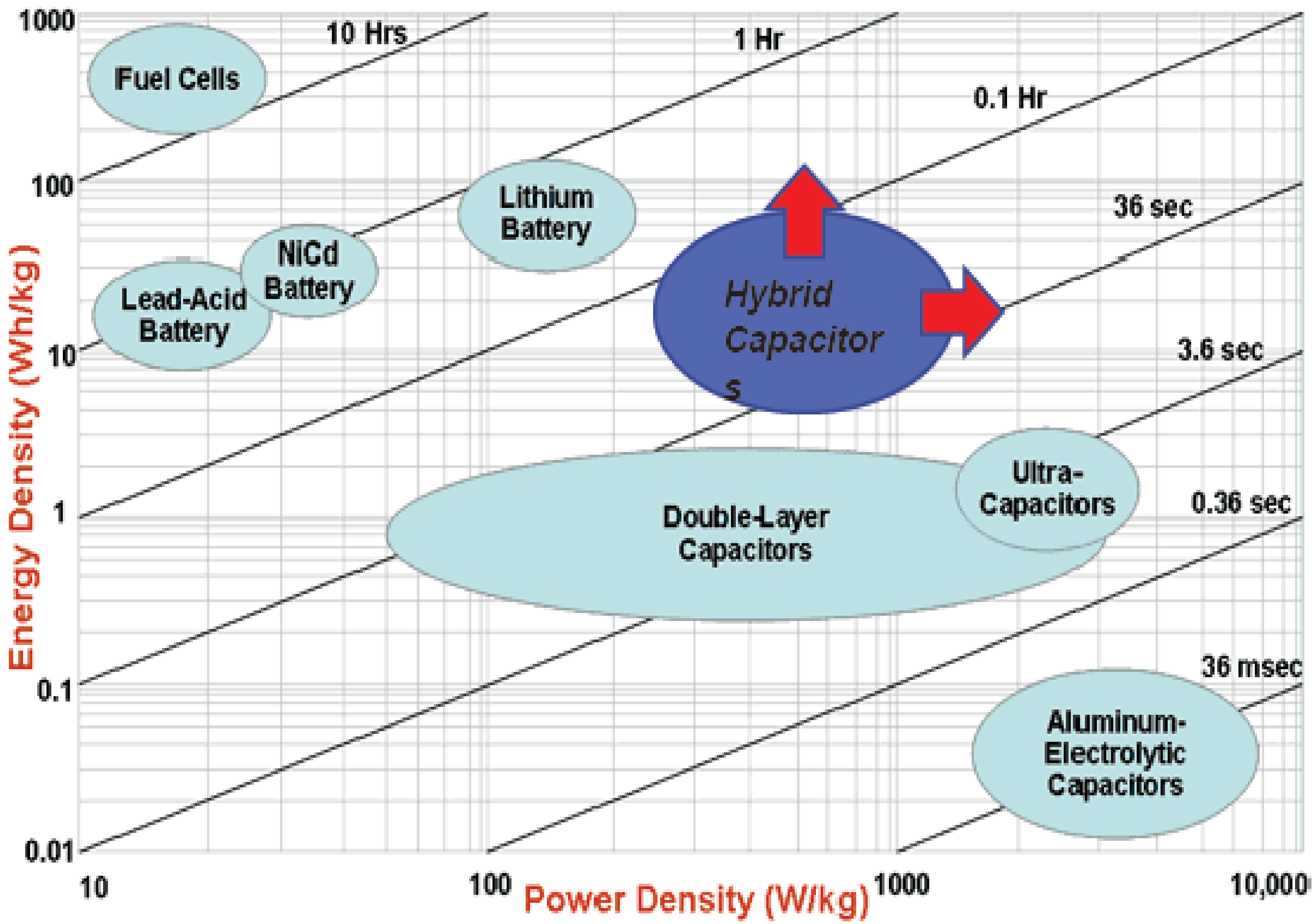
$$E = \frac{1}{2}CV^2 \quad \text{Eq. 1}$$

$$P = \frac{1}{4R}V^2 \quad \text{Eq. 2}$$

[1]. (Zhu et al.,2010)
[2] (Wang et al.,2010)
[3] (Liu et al., 2010)
[4] (Fernandez et al., 2008)
[5] (Moon et al., 2010)
[6] (Selverston, 2011)
[7] (Serway, 1998 p.602)
[8] (Zhu et al., 2011)

Source: IDTechEx

Ragone plot



Source US Defence Logistics Agency

Comparison of practical devices

Image	Device Type	Manufacturer	Capacitance	Voltage Rating	ESR (mΩ)	Total Energy Storage Capability	Maximum possible output power (load resistance=ESR)
	Supercapacitor	LS Mtron	3000 F	2.7 V	0.36	10.9 kJ	6.07 kW
	Electrolytic capacitor	Cornell-Dubilier	2200 µF	50 V	71	2.75 J	8.8 kW
	Hybrid supercapacitor	Samwha Electric	7500 F	2.8 V	0.8	29.4 kJ	2.45 kW
	Disposable energizer cell –C type	Energizer	8.35 Ah	1.5 V	324 mΩ	45.1 kJ	1.73 W
	Li-ion cell	Panasonic	3.4 Ah	3.6 V	50 mΩ	11.52 kJ	64.8 W

An overall comparison – Key specifications based

	Power density max	Energy density max	Cycles	Low temperature range
Li-ion battery	3 kW/kg	200 Wh/kg	500 - 1000	0°C to 60 °C
Supercapacitor	10 kW/kg	10 Wh/kg	1 000 000	-40°C to 80 °C
Hybrid supercapacitor	5 kW/kg	25 Wh/kg	>10 000	-20°C to 60 °C

Useful characteristics of SCs for analog and power electronic circuits

•They are approximately 20 to 100 times larger energy density than electrolytic capacitors

•Larger the SC, ESR is lower

•Typical ESR values are

- 30 to 100 mΩ for 0.1 to 2F capacitors (such as the thin profile Cap-XX types)
-
- 100 to 1000 mΩ for 1 to 100 F
- 0.3 to 2 mΩ for 600 to 5000 F devices

Source: Cap-XX , Australia

Smaller ESR of SCs – Useful in short term high power delivery

Traditional Applications of Supercapacitors

•In general supercapacitors have much less energy density than batteries

•But their power delivery capability (Watts/kg) is quite high compared to batteries

•Large supercapacitors have very low ESR in the range of few mΩs to fractional mΩs

Common supercapacitor applications are in

- UPS systems
- Wind turbine systems
- Electric vehicles/ Fork lifts/ Hybrid buses
- Utility voltage stabilizer systems
- Photo voltaic systems
- Memory back up systems

- In many of these applications battery-supercapacitor hybrid systems are used

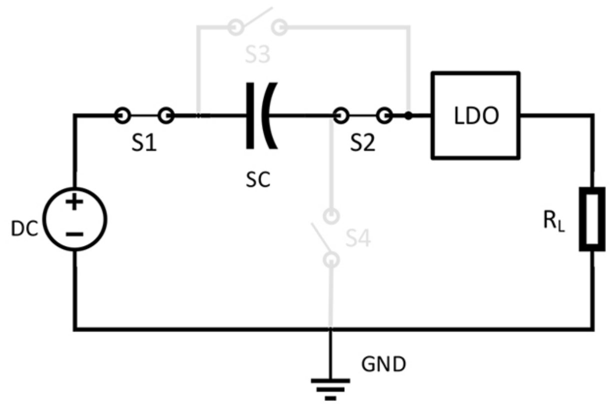
A unique new way to look at supercaps- Treat them as one million times larger devices compared to electrolytic caps!!!

Non-traditional applications of supercapacitors

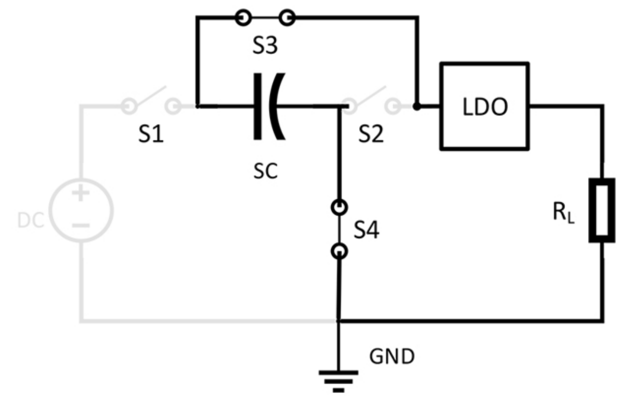
- When a SC is treated as a one million times larger capacitance with very low ESR multitude of new applications can be developed
- Few examples are
  - SC as lossless voltage dropper for high efficiency RFI/EMI free linear DC-DC converters – Patented SCALDO technique with built in DC-Ups capability
  - SC as a transient energy absorber for commercial surge protectors – Patented SCASA technique
  - Rapid water heating technique for domestic hot water supply – Patented SCATMA technique
  - SCALED technique for DC lighting in DC-Microgrid systems
  - SCAHDI technique for high performance solar inverters
- The above techniques are generally known as Supercapacitor Assisted (SCA) techniques developed at University of Waikato, New Zealand

In developing SCA techniques for commercially useful novel applications, research team has looked at a SC as very large capacitor with a negligible ESR – leading to multiple international patents and publications

The SCALDO Technique



Capacitor as a voltage dropper



Powering Load with charged capacitor

- Load receives the low-noise and high-current slew rate capable DC output of a linear regulator
- End to end efficiency is improved by a factor of 2 to 3 [for a 12-5 V case efficiency is two times improved]
- Switching frequency is extremely low (Fractional Hz to few Hz)
- RFI/ EMI issues are eliminated
- Output currents ranging from mA to over 100 A
- DC-UPS capability

The above approach allows to design a linear DC output converter with an energy re-circulation frequency, typically in the range of millihertz to fractional hertz

Practical implementation of the SCALDO technique

- SCALDO technique allows you to build very high efficiency linear regulators

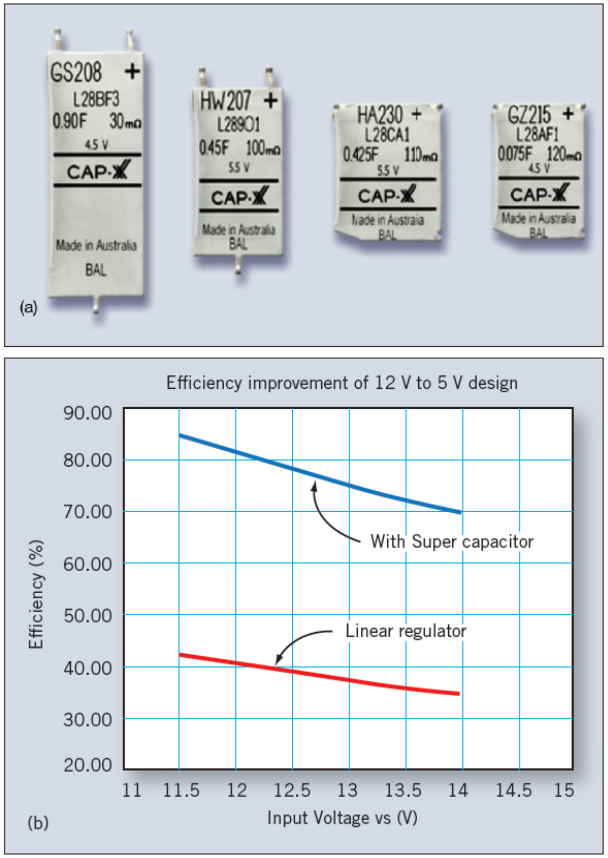


Fig. 3(a) Capacitor size reductions in an early prototype for 12-5V regulator super-caps used. (b) Shows efficiency improvements in 12-5 V regulator supercaps.

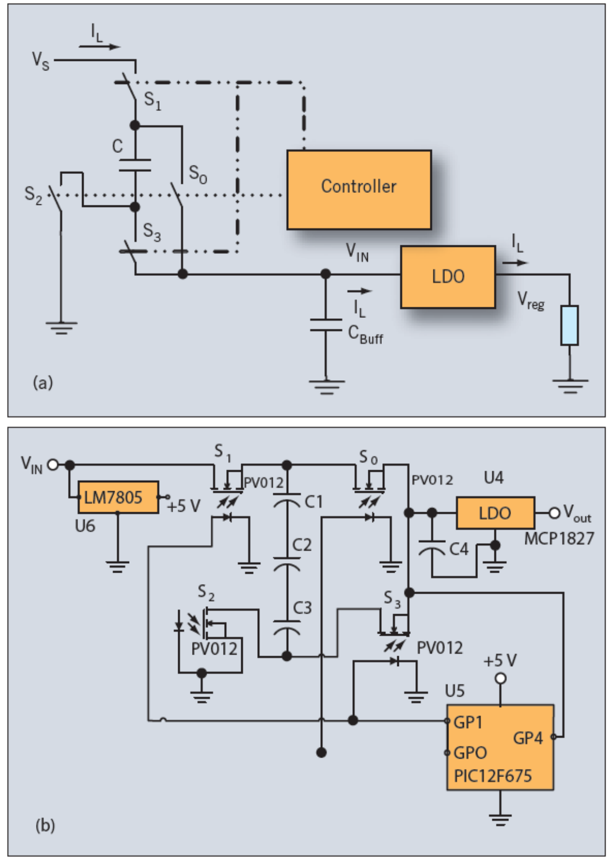
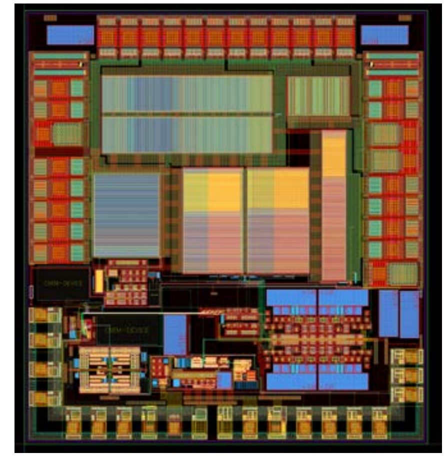


Fig. 4(a) The 12 V to 5V circuit to achieve efficiency improvements shown in Fig. 4(b). The implementation in Fig. 4(b) is shown using a PIC microcontroller.



SCALDO technique in IC implementation

In a typical SCALDO circuit such as this 12-5V converter we get an efficiency improvement factor of 2

SCALDO variations

RS-SCALDO technique for high current converters

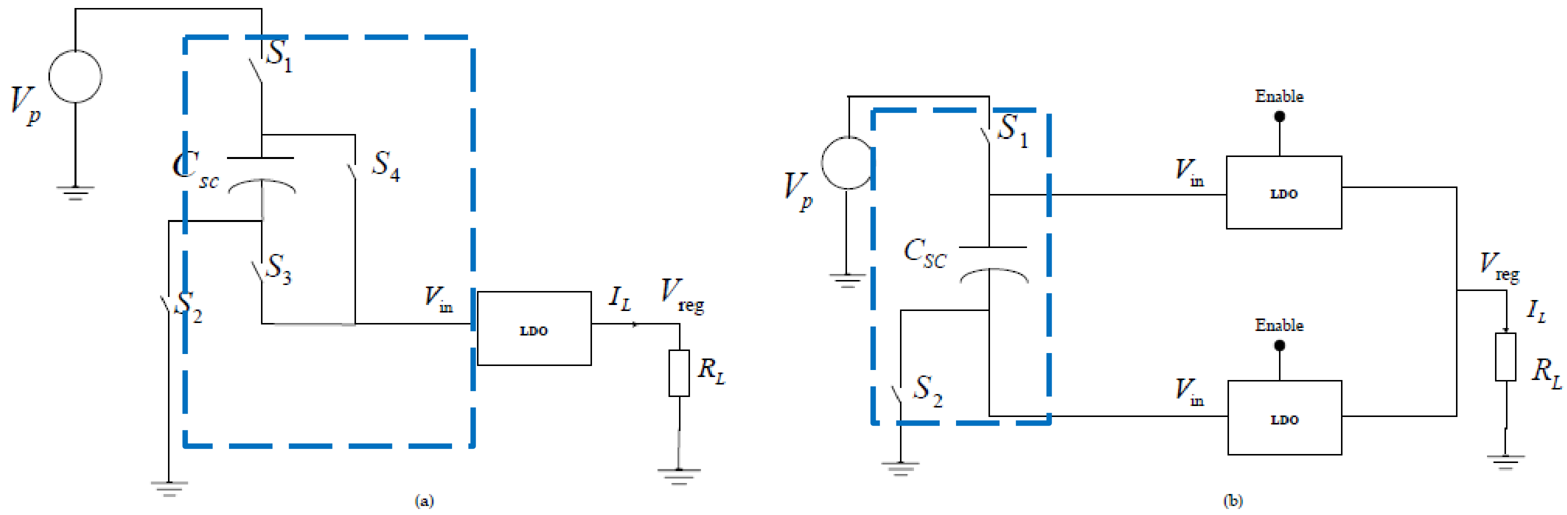


Figure 1.1: (a) Basic SCALDO configuration with single LDO and 4 switches (b) Modified RS-SCALDO (Reduced switches) configuration with two identical LDOs and two switches

By splitting the LDO into two half size LDOs we can reduce the number of powers switches

Basis for linear VRM systems!

Another variation is the dual-output SCALDO [**Do-SCALDO] for dual rail DC-DC converters**

Surge protectors based on supercapacitors: SC Assisted Surge Absorber (SCASA) Technique

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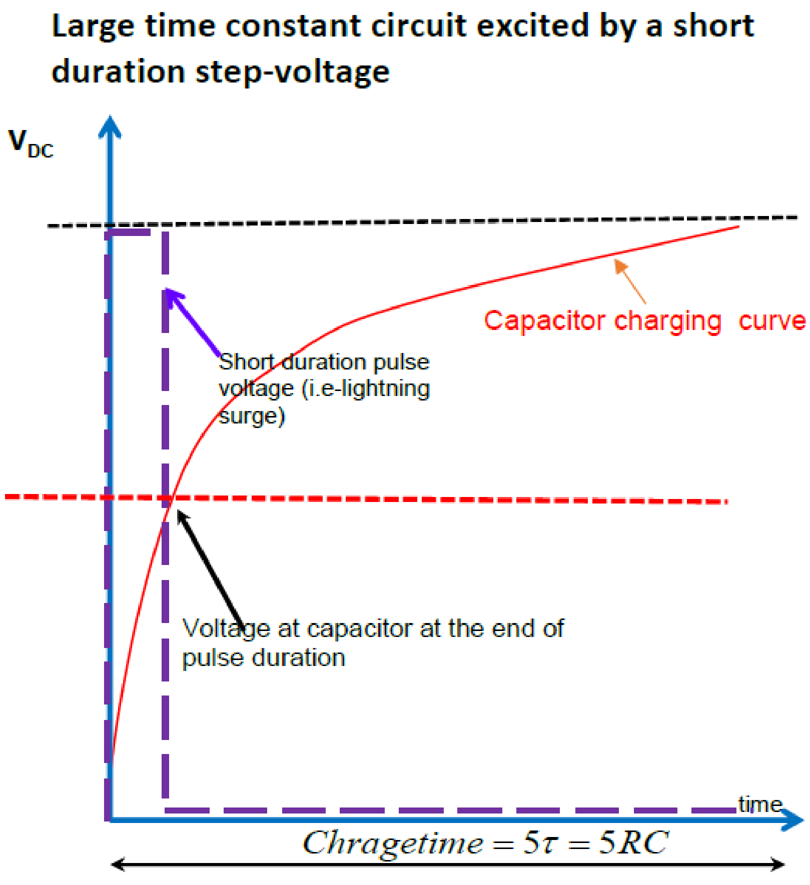
Surge Capability Testing of Supercapacitor Families Using a Lightning Surge Simulator

Nihal Kularatna, *Senior Member, IEEE*, Jayathu Fernando, Amit Pandey, and Sisira James, *Student Member, IEEE*

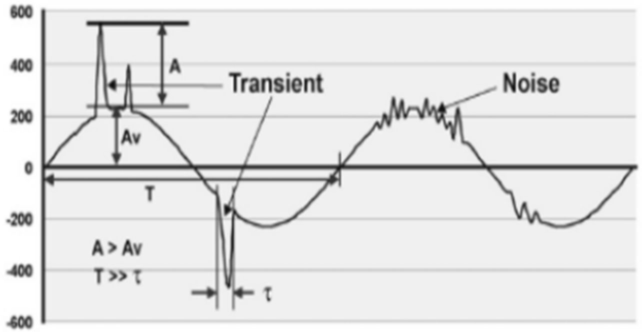
Despite their low DC voltage rating, supercapacitors are large time constant circuits



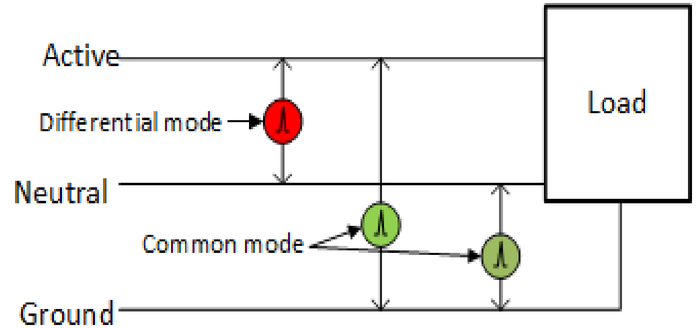
- A typical SC circuit has a time constant from milliseconds to seconds
- 1 F SC with an ESR of 100 mΩ will have a time constant of 100 ms
- Such a circuit will take about 0.5 seconds to charge the capacitor to DC source voltage
- However, if the source voltage lasts only 10-100 µs (as in a case of a lightning induced case) capacitor will not charge to a significant voltage

Can SCs absorb high voltage transients like lightning surges/inductive energy dumps induced on power rails?

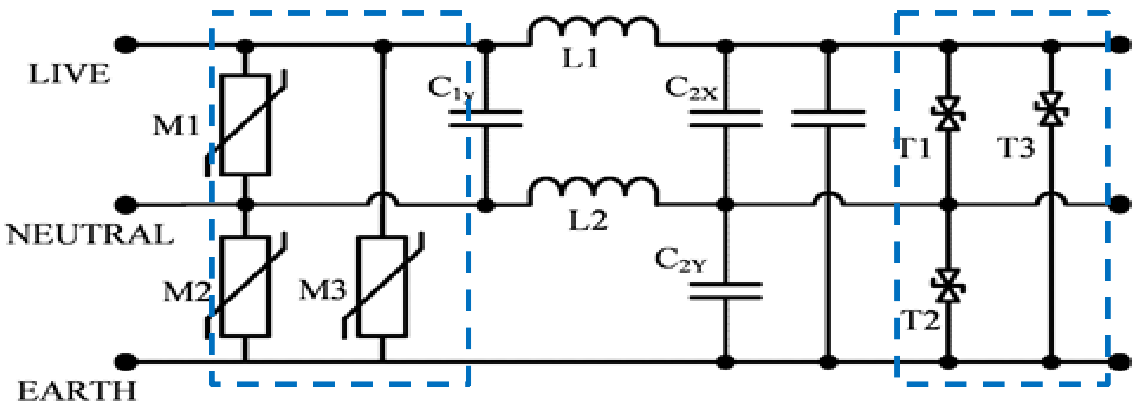
Typical surge protector circuits and power line transients



Power line surges



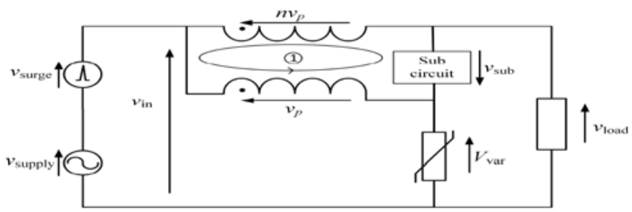
Differential and common mode surges



Typical surge protection circuit

Typical surge protectors use MOVs and BBDs to absorb surge energy. However, they are transient rated devices, and if repeated surges occur they tend to get destroyed.

SCASA Technique



SCASA Technique with a SC sub-circuit for better surge absorption

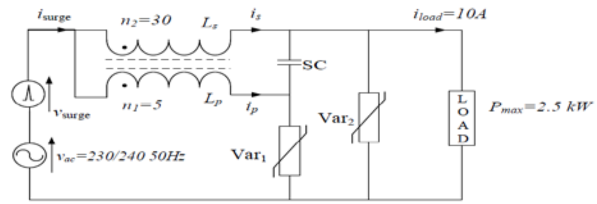


Figure 5.16: The SCASA technique with an additional second varistor for further protection

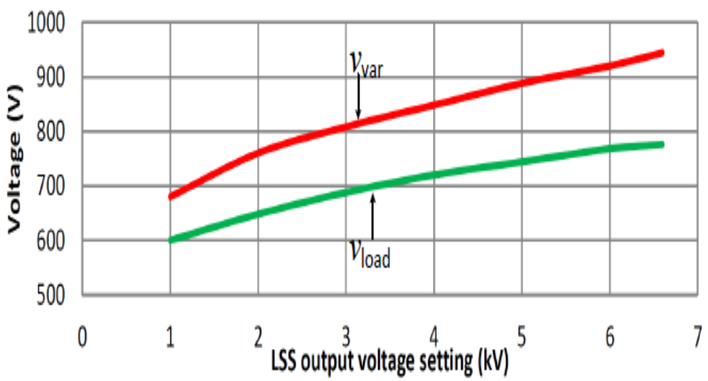
Practical implementation in a commercial design

Commercial product based on SCASA technique

SCASA advantage over well-known surge absorber techniques

Table 5.4: Component count comparison for differential-mode section in commercial surge protectors vs SCASA

Component type	High end	Low end	SCASA
MOVs	4	1	2
Inductors	2	0	1
X-type capacitors	5	1	0
Supercapacitors	0	0	1



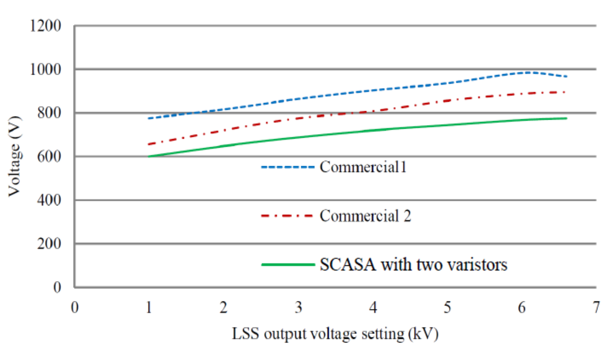


Figure 5.19: Performance comparison of SCASA with two commercial surge protectors

In SCASA, number of components are less and the transient related voltage at the protected load is less than the clamping voltage at the MOV

Supercapacitor Assisted Temperature Modification Apparatus (SCATMA) : A SC based solution to hot water delay issue

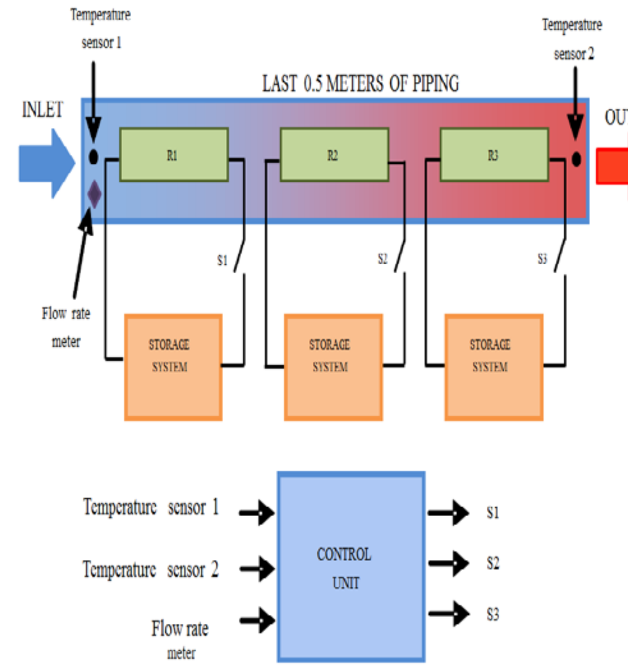
Well-known problem at water faucets

- In our home environments central water heater is at a distant location from individual faucets
- This makes cold water storage between the central heater and the faucet
- Result is delayed hot water at the faucet
- Delay can be anything from about 10 seconds to a minute depending on the length of the buried pipes
- This creates a huge waste of water, every day

Why it is not easy to solve the problem

- Maximum power we can draw from a wall socket is about 2.3 kW
- Water is not stationery and hence heating power deliverable into water should be at a value much larger than 2.5 kW maximum
- Building heaters and tanks to do this is complex and costly
- Safety/ regulatory issues

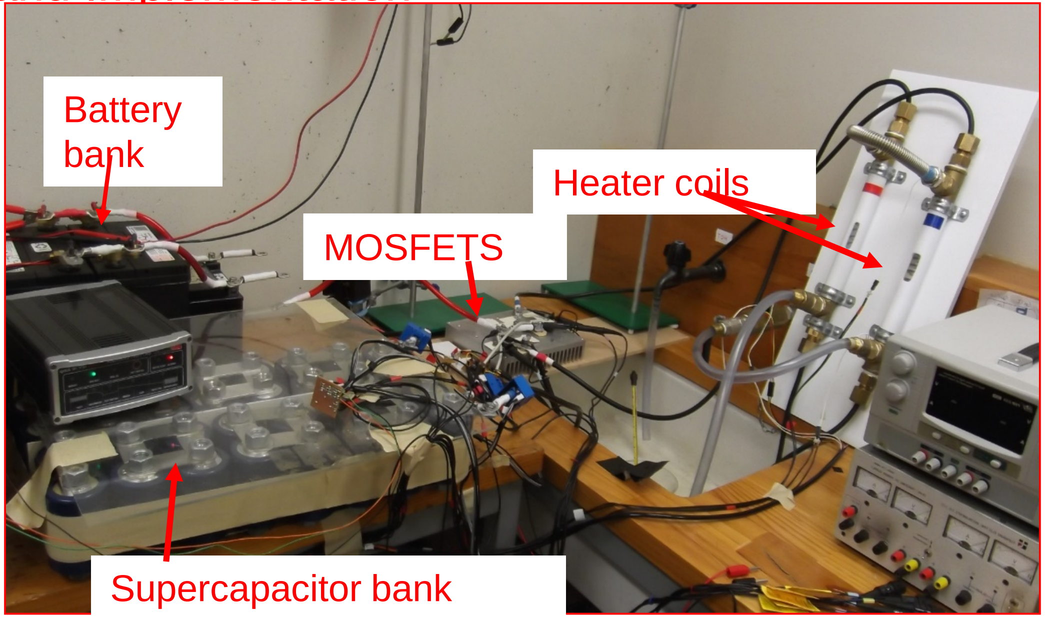
Instant water heating : **SCATMA**

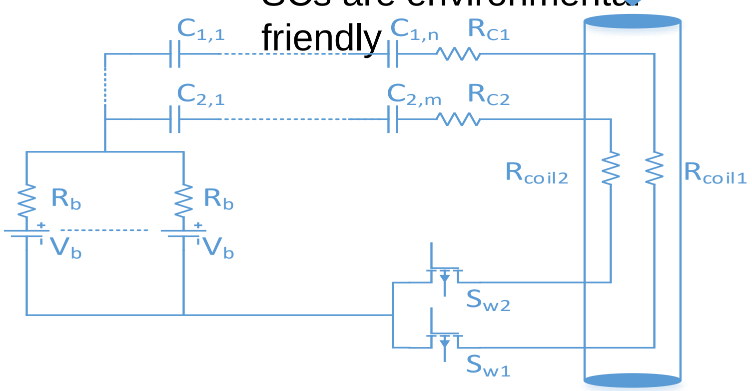


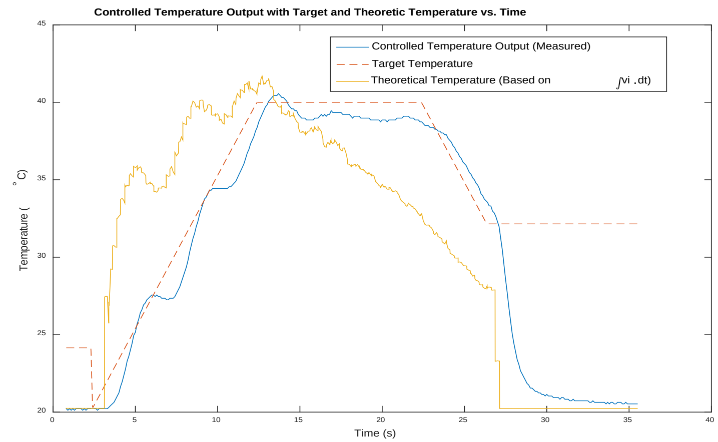
Flow Rate ($L\,min^{-1}$)	4			6		
Temperature Rise (°C)	20	30	50	20	30	50
Total Energy (W h)	46	70	116	70	105	175
Average Power (kW)	5.6	8.4	14	8.4	12.6	21
Average Current at 50 V (A)	112	168	280	168	252	420

Design Approach and Implementation

- Energy Storage System
  - Supercapacitors (SC) vs. Batteries
    - Neither media has both high energy density and power density
    - Superior cycling capability of SC- but with low power density
    - Constant lower ESR of SCs allow high currents at lower depth of discharge
    - SCs are environmentally friendly

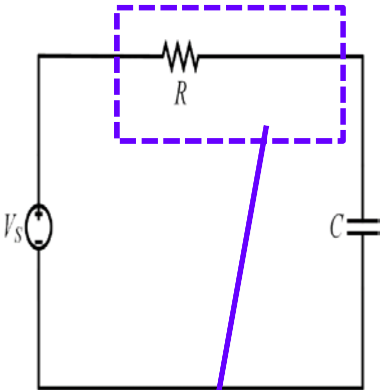






In first prototypes, to lower the cost, a battery-SC hybrid solution had to be used.
However with new hybrid SCs SC only solution is feasible.

Inserting a useful resistive load in the charging path to circumvent the loss



- The useful resistive load (R_L) can be;
  - Lighting load
  - Inverter
  - Any resistive load
- Losses in each resistive element ;

$$E_{r_b} = \left(\frac{r_b}{r_b+r_l+r_c+R_L}\right) . E_{Loss}$$

$$E_{r_l} = \left(\frac{r_l}{r_b+r_l+r_c+R_L}\right) . E_{Loss}$$

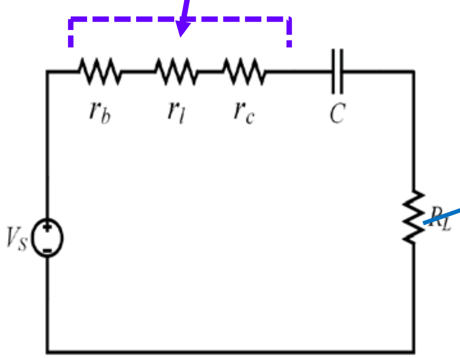
$$E_{r_c} = \left(\frac{r_c}{r_b+r_l+r_c+R_L}\right) . E_{Loss}$$

$$E_{R_L} = \left(\frac{R_L}{r_b+r_l+r_c+R_L}\right) . E_{Loss}$$

- The R_L utilizes the wasted energy;

Simple RC circuit where resistive losses could waste energy up to a 50%

$$E_{Loss} = \frac{r_b+r_l+r_c}{(r_b+r_c+r_l)+R_L} \times 50\%$$

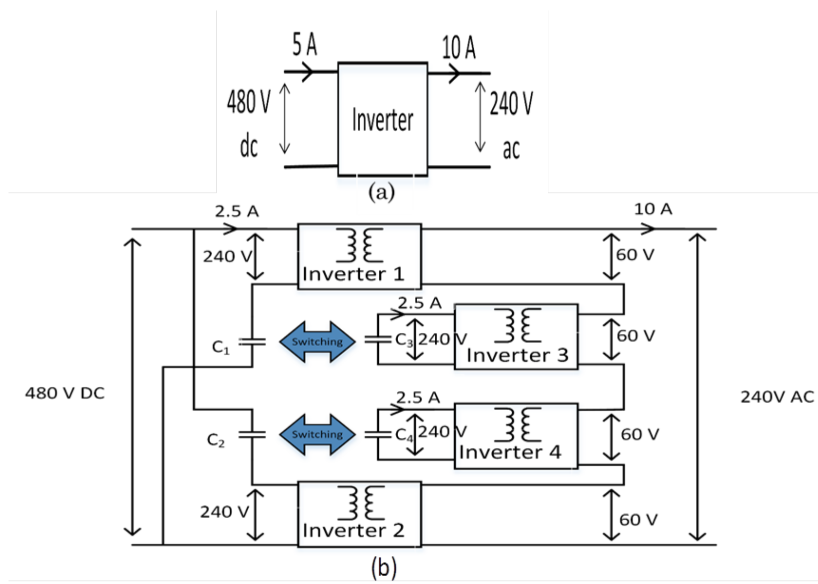


Inserting useful resistive load in the charging loop

This concept was used in the SCALDO technique, where R_L was the loaded LDO

SC assisted high density inverter(SCHADI) technique

- A loaded inverter is used in the charging path of a SC bank in an inverter system
- The overall inverter is divided into several micro-inverters
- Outputs are series connected to get the required AC voltage
- SC banks keep powering half the micro-inverters
- Other half are directly powered through the charging loop



In SCAHDI also we use a SC and a useful resistor to circumvent losses

Conclusion

- When a capacitor becomes almost a million times larger it can be creatively used for very new circuit topologies and techniques
- These new techniques can help in
  - Reducing lost energy in power converters
  - Developing new surge protectors with low component count and better performance
  - Low voltage rapid energy transfer into flowing liquids
  - High density inverters
  - DC Microgrid applications for energy efficiency

What was presented is only the tip of the ice burg… Creative circuit designers can use EDLCs in much more versatile ways than in simple energy storage systems….

Thank you…..

Question Time…