Ins and Outs of Commercially Available Supercapacitors

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Presentation outline

- What is a supercapacitor
- Basic properties of commercial devices / Ragone plot
- Different types of commercial supercapacitor and their properties
- Discharge characteristics of different types
- Traditional versus non-traditional applications
- Few examples of non-traditional techniques and SCALoM theory
- Future possibilities
- Conclusion

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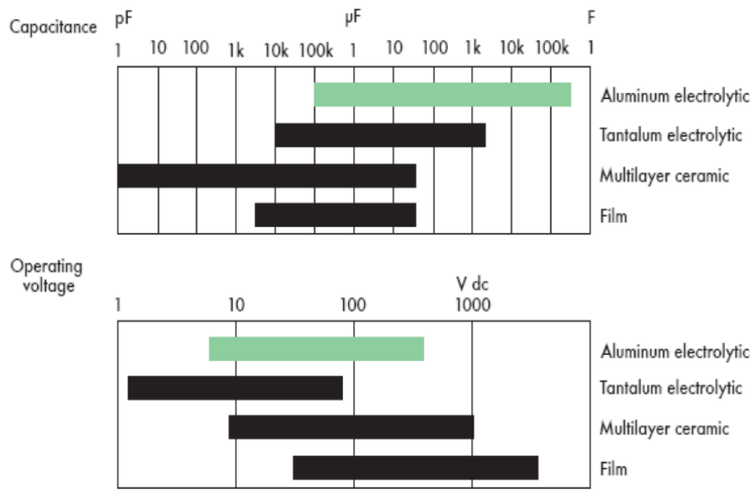
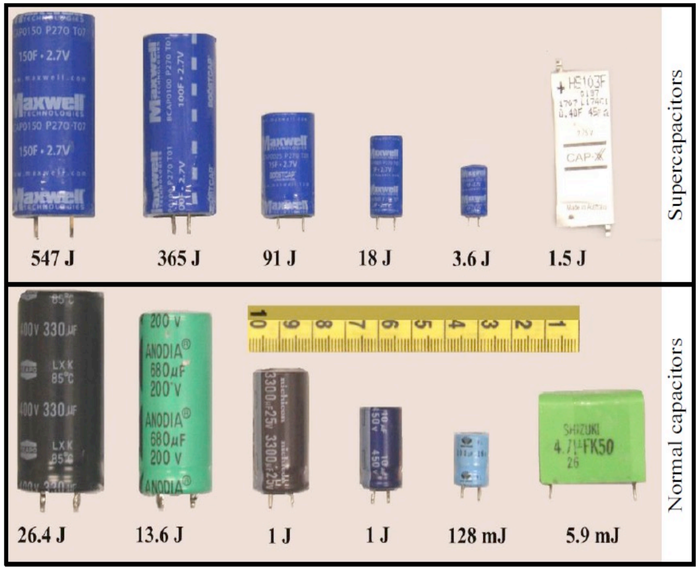
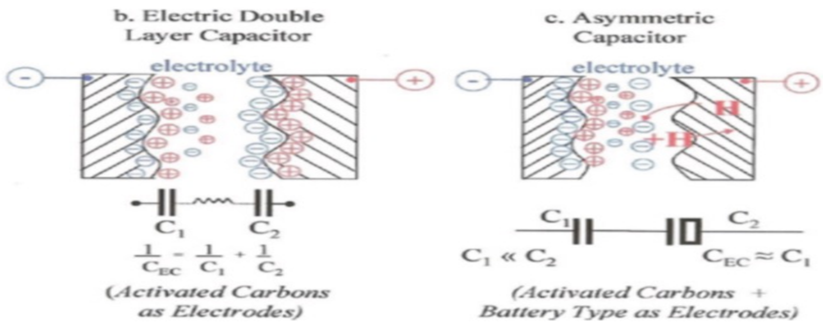
Normal capacitors and their limits

Physical Comparison of Supercapacitors (SC) and Electrolytic Capacitors



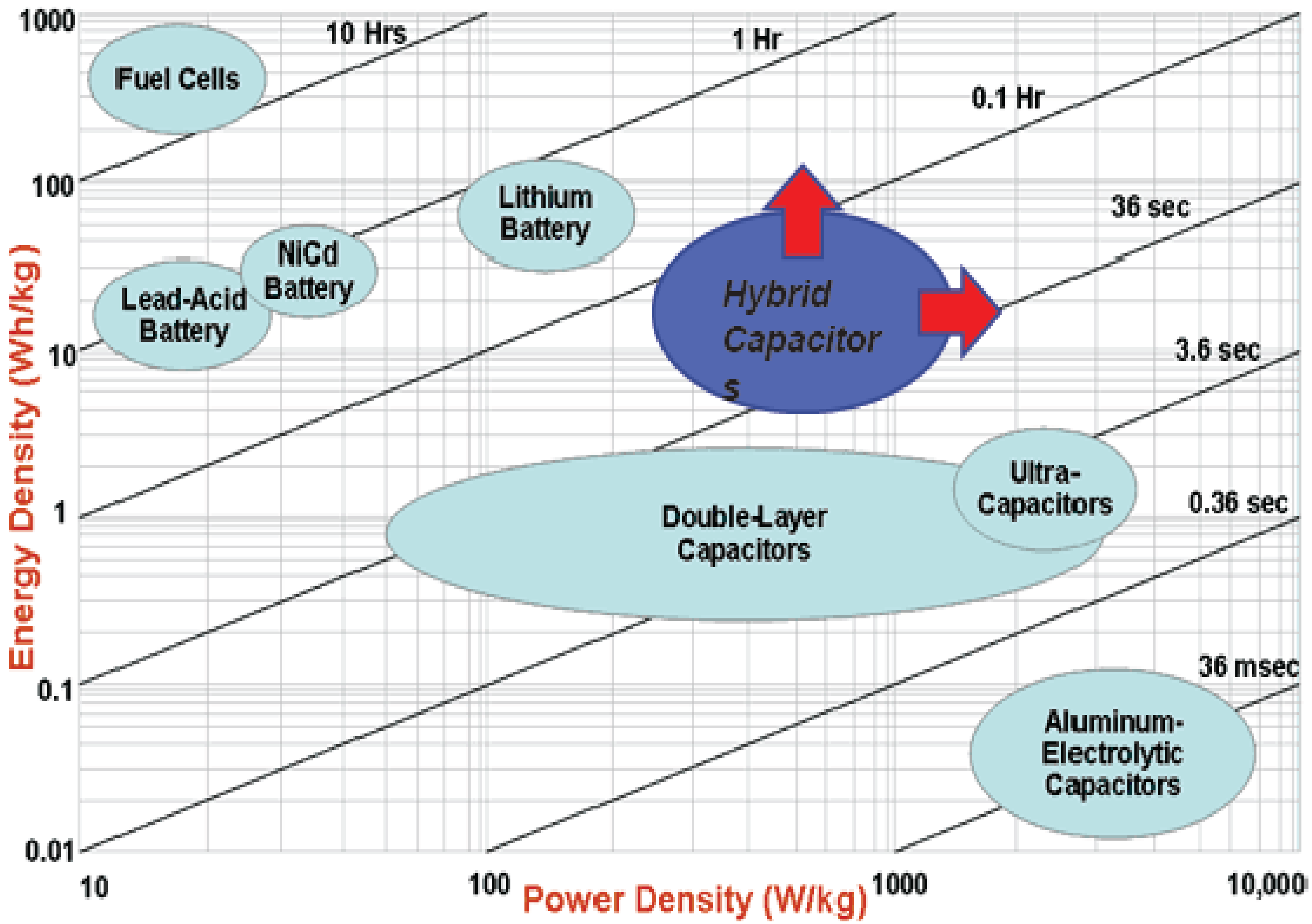
2. Common dielectric materials, i.e., aluminum oxide, tantalum tetroxide, titanium oxide barium, and polyester polypropylene, also pose limits on capacitance level and operating-voltage capabilities.





Typically, in SCs we get approximately *one million times bigger capacitance*, but at the penalty of very low DC voltage rating

Ragone plot



Source US Defence Logistics Agency

Commercially available supercapacitor types

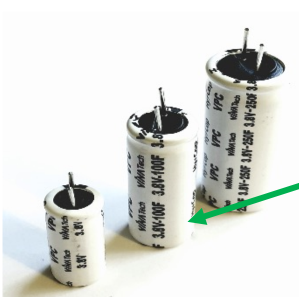
- There are few basic types
  - Symmetrical double layer capacitors
  - Hybrid types with one battery type electrode
  - Capa-batteries
  - Lithium SCs

Sources : Samwha Electric

- Early versions were symmetrical double layer capacitors ***[3.7Wh energy capability example]***

Then hybrid devices with one electrode similar to Li-ion batteries were commercialized ***[8.2Wh energy capability example]***

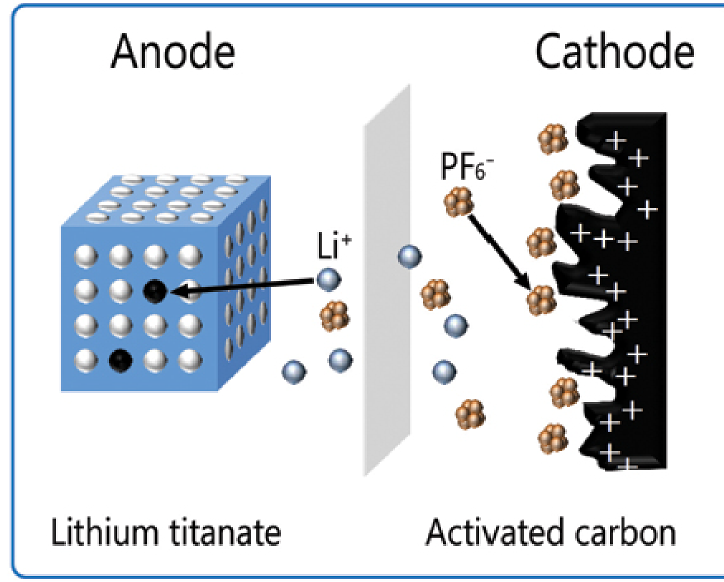
More recently capacitor-batteries were introduced ***[40 Wh energy capability example]***



Lithium supercapacitors [Source: Vinatech]

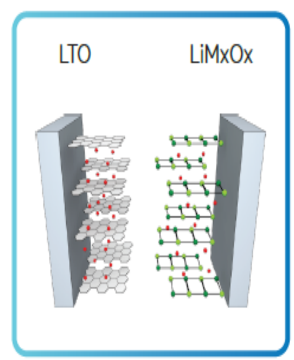
Hybrid supercapacitors

- They usually have 2.5 times higher energy density than symmetrical double layer capacitors with activated carbon electrodes
- Higher power density and longer term reliability compared Li-ion batteries
- Cathode is activated carbon based – Electrostatic Adsorption-desorption based
  - High surface area
  - High power capability
- Anode is Lithium Titanate based- Oxidation-reduction based
  - High energy performance
  - Zero-stain insertion of Li ion
- Operating voltage range is from 2.8 to 1.5 V



Battery capacitors

- It utilizes the negative LTO electrode and the positive Li transition metal oxide electrode employing Li+ intercalation-deintercalation process.
- These have now reached the energy density of lead – acid batteries
- Operating voltage range is from 2.7 V to 1.6 V approx.
- Cycle life is less than hybrid types

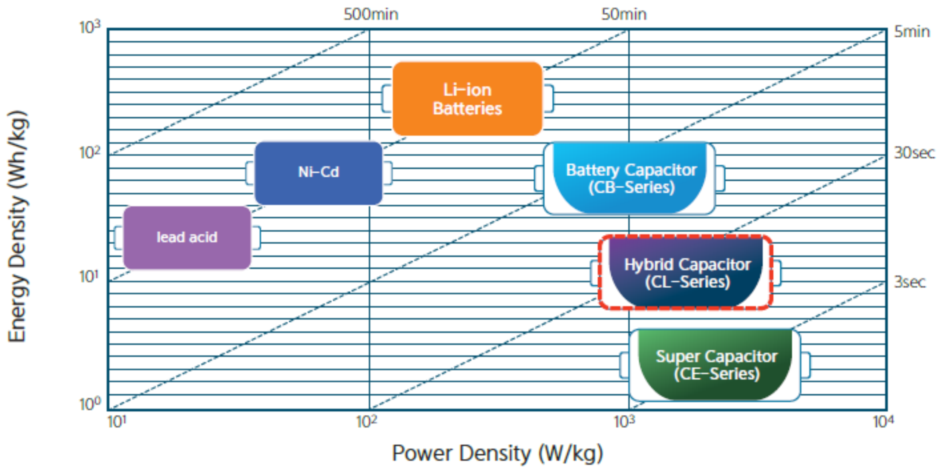


Charging Mechanism : Chemical
Energy Density : 50~120Wh/L
Power Density : 1,600~3,200W/L
Cycle Life : 15,000~20,000cycles

Comparison of supercapacitor types and rechargeable batteries

Parameter	Symmetrical SCs	Hybrid SC	Capa-batteries	Lead –Acid	Li-Ion
Energy density (Wh/kg)	3-8	7-14	50-120	50-125	250-670
Power Density (W/kg)	8000	2500-4000	1600-3200	25-100	375-1750
Cycle life	1,000,000	40,000-50,000	15,000-20,000	500-2,000	1000-1200
Rated voltage per cell (Volts)	2.5- 3.0	2.7-2.8	2.7	2	3-3.6
Capacitance (F)	1-5000	200-7500	1000-100,000	-	-
Temperature range (^{0}C)	-40 to 60	-20 to 60	-20 to 50	0 to 40	-10 to 50

Battery versus SC

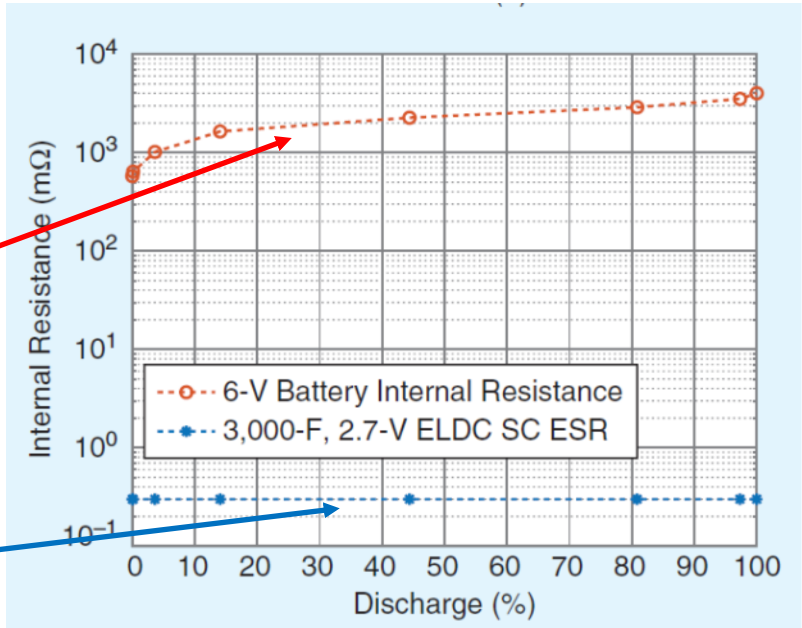


Source: Samwha electric

- Capa-batteries gradually reach the energy density of lead-acid batteries

In a battery internal resistance increases with % discharge

But a SC's ESR remains relatively constant with % discharge



Comparison of internal resistance: Battery versus SC

Discharge characteristics of different SC types-
Constant Resistance case

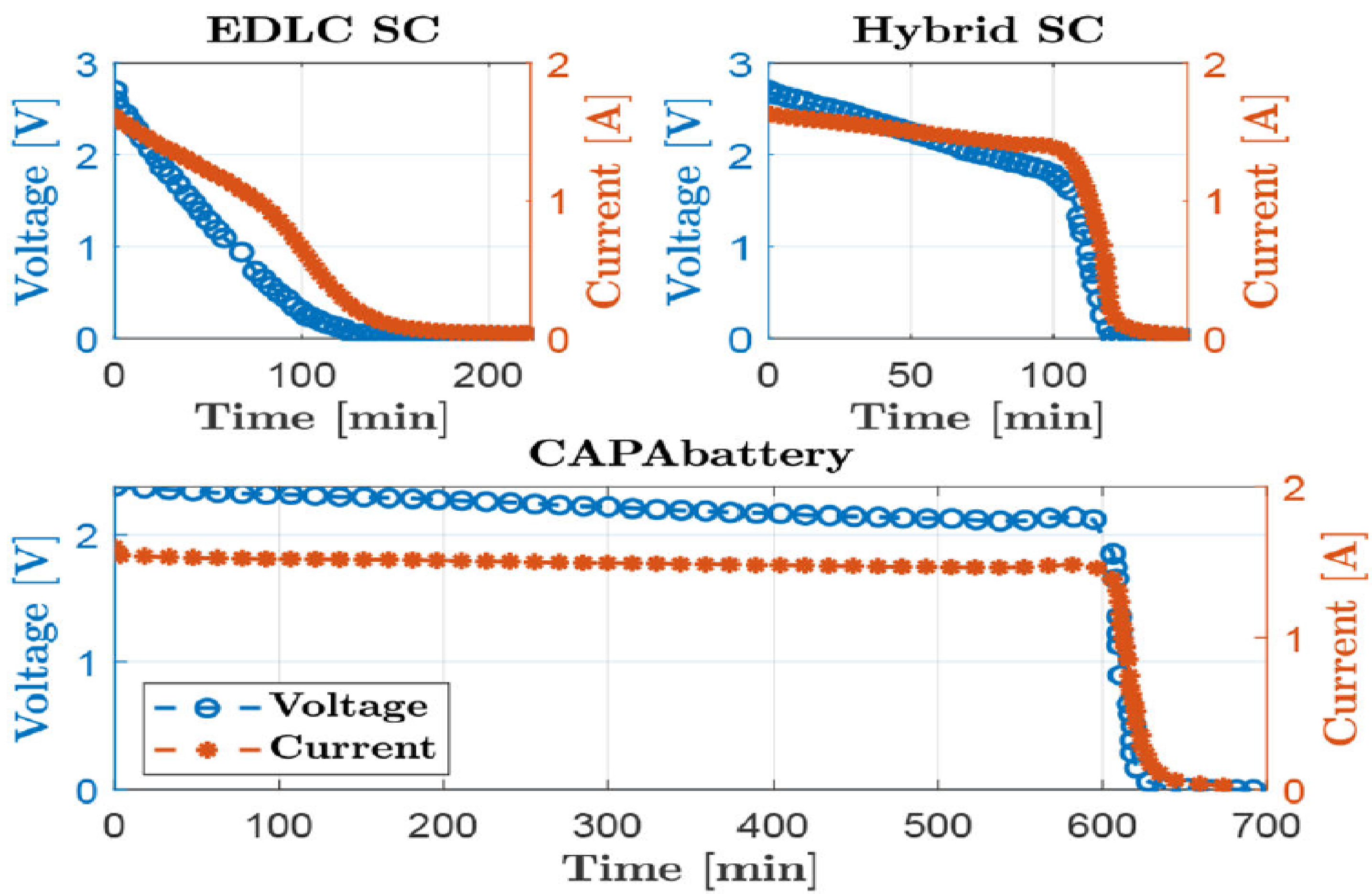
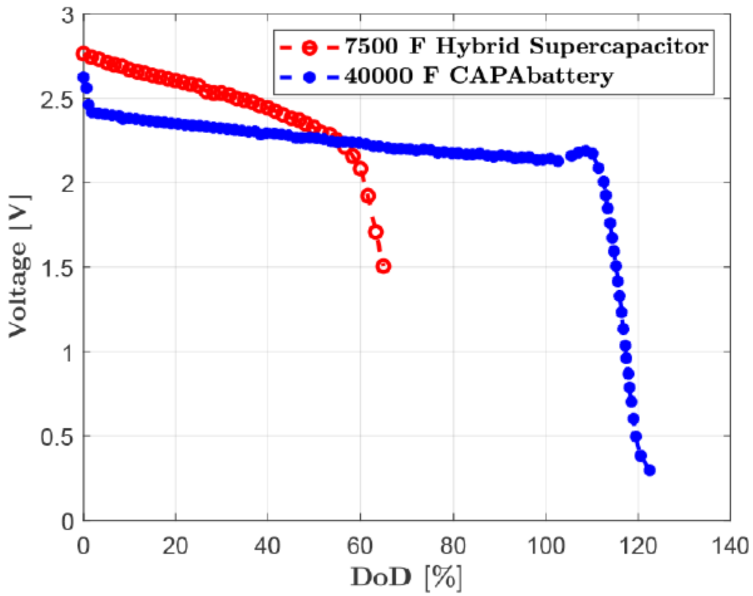


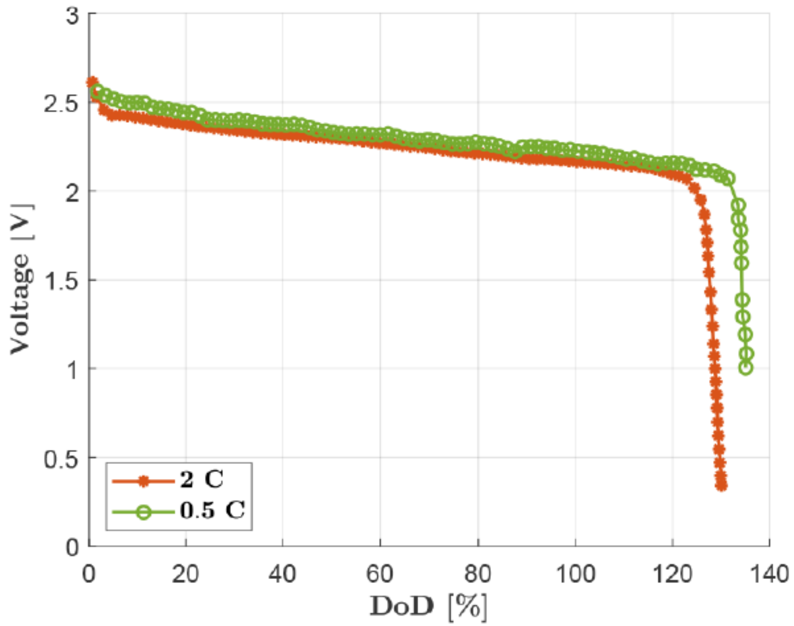
Fig. 5 *Discharge curves for three SC technologies for constant resistance (devices tested were 3000 F, 2.7 V EDLC SC, 7000 F, 2.7 V hybrid SC and 40,000 F, 2.8 V CAPAbattery respectively)*

Discharge at constant current rate



Discharge of a hybrid cap and capa-battery at 1 C rate.

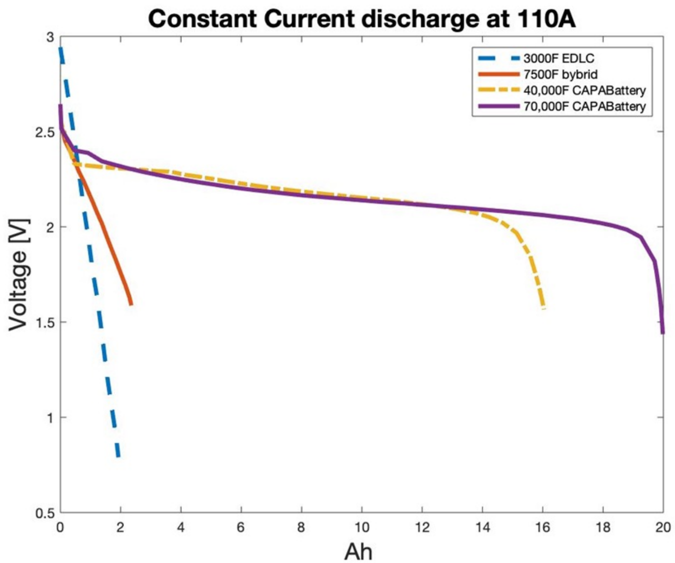
7500 F hybrid is considered as a 2.4 Ah cell and 40,000 F capa-battery is considered as a 12.2 Ah cell.



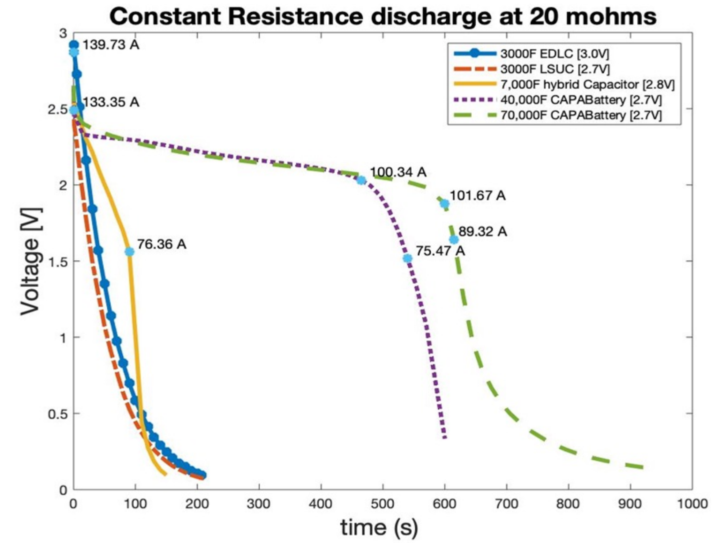
2 C and 0.5 C rate discharge of the 40,000 F capa-battery

- Symmetrical SCs behave as capacitors, with a slight non linear behaviour of capacitance at different voltages.
- However, hybrid type devices tend to show battery type discharge curves.

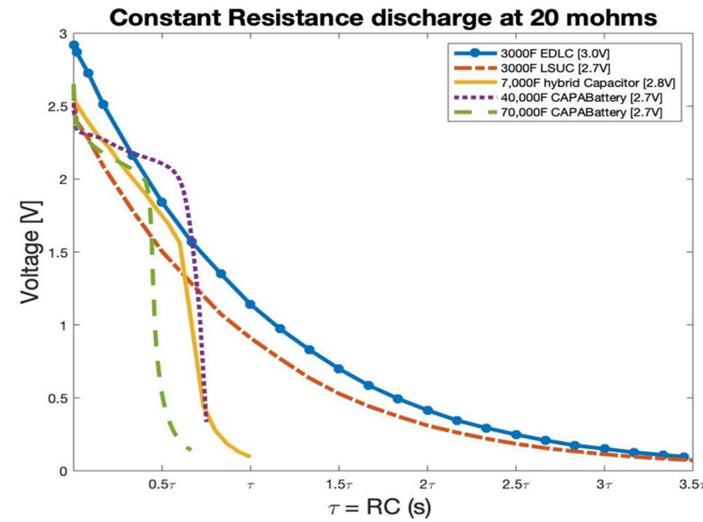
Comparison of different families



Constant current discharge at 110 A for different types of supercapacitors



Constant resistance discharge using a 30 mΩ resistor (a) voltage versus time in seconds



Constant resistance discharge using a 30 mΩ resistor (a) voltage versus time in units of time constant (τ=RC)

Temperature capability and charging efficiencies

	Symmetrical Supercapacitors	Hybrid supercapacitors	Battery capacitors	Li-ion battery
Charging method	Physical	Physical-chemical	Chemical – physical	Chemical
Operating temp range	-40^{0}C to + 60^{0}C	-20^{0}C to + 40^{0}C	-20^{0}C to + 50^{0}C	-10^{0}C to + 50^{0}C
Charge-Discharge efficiency	≈100%	≈100%	≈90 -100%	70% -85 %
Cycle life	Over 500,000	Over 50,000	Over 20,000	1000-1500

Given the case of high cycle life compared to li-ion batteries sC based energy storage systems are more effective on a longer-term perspective, and they can be considered fit and forget devices, and better tolerance for freezing temperatures

Non traditional applications of supercapacitors

Traditional applications of commercial SCs

- Supercapacitors
  - solar and renewable energy systems
  - Emergency lighting
  - Consumer electronics
  - Industrial machinery
  - Automotive
  - UPS systems
- Hybrid SCs
  - solar and renewable energy systems
  - Emergency lighting
  - Consumer electronics
  - Audio systems
  - Industrial machinery
  - Automotive
  - UPS systems
- Capa-batteries
  - solar and renewable energy systems
  - Consumer electronics
  - Audio systems
  - Industrial machinery
  - Automotive
  - Transportation
  - UPS systems

If we consider the large capacitances combined with low ESR of the supercapacitors, designers can see a whole new range of **non-traditional applications**- particularly the symmetrical supercapacitors.

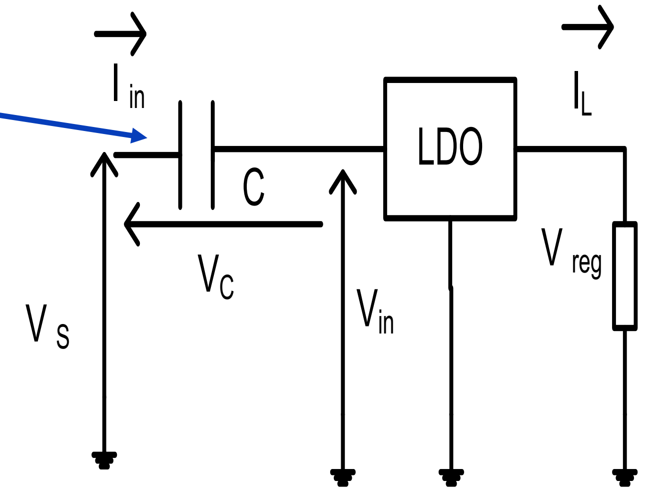
These can be used in power converters and protection systems useful in renewable energy applications.

Examples are very low frequency DC-DC converters, surge protection systems and rapid energy delivery systems

Supercapacitor Assisted Low Dropout (SCALDO) regulator technique

An LDO is a linear regulator, where input to output voltage difference is low, to keep the efficiency high. We can combine this with a small SC in series, which will cat as a lossless dropper to form a very low frequency DC-DC converter without RFI/EMI

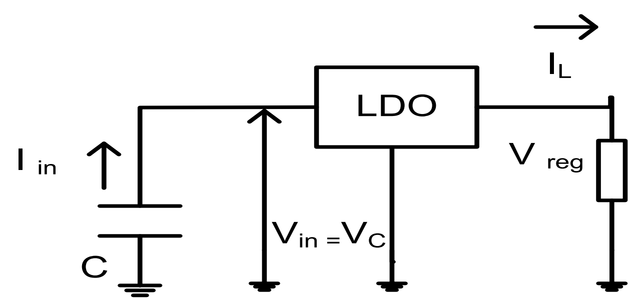
Now let us insert a SC pre-charged to Vc in the series path …



LDO's efficiency will be V_{reg}/V_{in} , but input voltage now is $V_{in} + V_C$

When load current, I_L is drawn through the SC its voltage keeps increasing while V_{in} keeps dropping

Given the size of the capacitor it will be a slow process, and when V_{in} drops to minimum, we can connect the capacitor to LDO directly, and disconnect the input supply (as per lower Figure)



When V_c goes below V_{in} min the circuit will return to series configuration (as per upper figure)

The above approach allows us to develop a high-efficiency 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

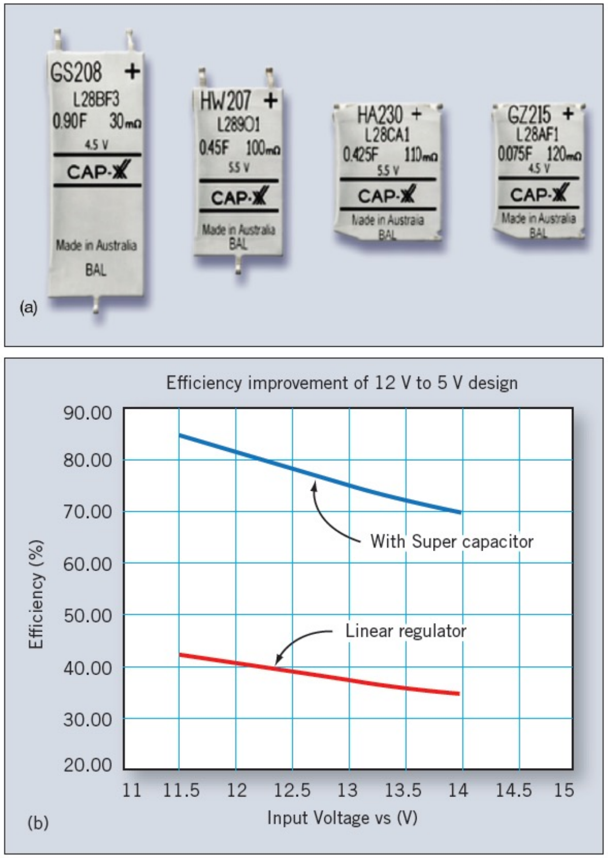


Fig. 3(a) Capacitor size reductions in an early prototype for 12-5V regulator super-caps used. (b) Shows efficiency improvements in 12-5 V regulator supercaps.

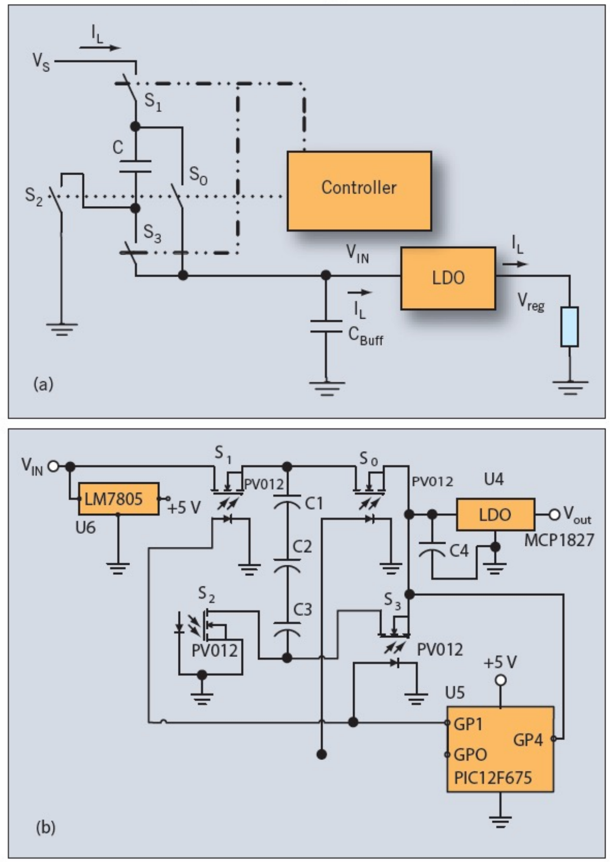
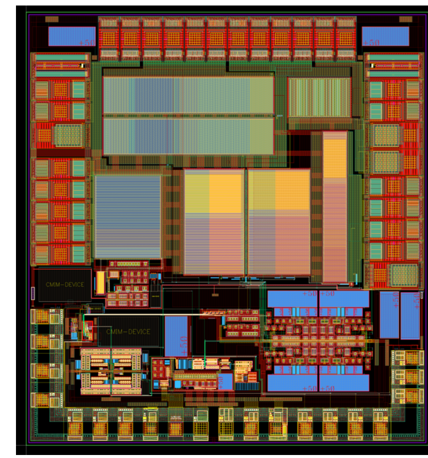


Fig. 4(a) The 12 V to 5V circuit to achieve efficiency improvements shown in Fig. 4(b). The implementation in Fig. 4(b) is shown using a PIC microcontroller.



SCALDO technique in IC implementation

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

Ref: (2014) Kankanamge, K., Kularatna, N., Improving the end-to-end efficiency of DC-DC converters based on a supercapacitor assisted low dropout regulators (SCALDO) technique, IEEE Transactions on Industrial Electronics, Vol 61, Iss 1, January 2014, pp 223-230

A summary on SCALDO technique

- SCALDO is a high efficiency linear DC-DC converter
- It provides the hall marks of a linear converter, while eliminating the low efficiency of a straight linear converter
- No RFI/EMI filters needed since energy recirculation happens at fractional Hz frequency
- By over-sizing the SC DC-UPS capability can be added to the converter
- It can be extended to many applications
  - Split rail high efficiency linear converters
  - High current DC power supplies
  - 48 V Google new architecture power supplies
  - AC input based high efficiency isolated power supplies
  - Renewable energy DC-DC converters
- It is not a variation of switched capacitor converters[1] ---

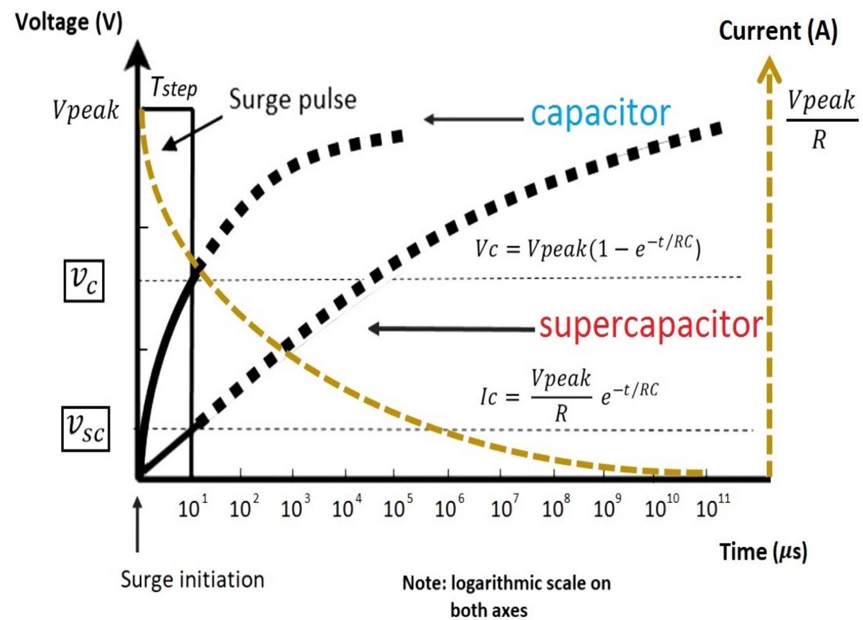
1. Ref -Kankanamge, K., Kularatna, N., Supercapacitor assisted LDO (SCALDO) technique-an extra low frequency design approach to high efficiency DC-DC converters & how it compares with the classical switched capacitor converters, Proc of 28th Annual IEEE-APEC-2013, pp 1979-1984.

Supercapcitor based techniques for transient surge absorbers

SC Assisted Surge Absorber (SCASA) Technique

Advantage of a long time constant SC circuit in absorbing surge

- All transients have time durations of microsecond order timings, with kilo-volt order peak voltages
- An R-C circuit, subjected to a **step DC voltage [of 1000 V]** , generates an exponentially growing DC voltage and exponentially decaying loop current.
- If R=1 Ω and C = 1 μF, τ= 1 μs and capacitor could reach maximum voltage after approx 5 μs
  [In Figure T_{step} >> 5 μs]
- Max energy stored in capacitor
  = $0.5*1*10^{-6}*(1000)^2$ =0.5 J Energy dissipated in resistance of the loop is also 0.5 J.
- Capacitor should be able to with stand 1000 V
- However, if we **replace the normal cap with a SC of 1 F** (and DC voltage rating of 2.5 V) time constant jumps to 1 sec.
- Now if the duration of the step pulse is only say 10 μs,
  - Capacitor develops a voltage of much smaller value (about 0.1 mV only)
  - Resistor will dissipate approx. ($1000^2*10*10^{-6}$ ≈10 J)
- SC has a energy storage capability of $0.5*1*(2.5)^2$ =3.12 J
- What capacitor accumulates is only [$0.5*1*(0.1*10^{-3})^2$ ≈ 0.05 μJ



All what this tells us is the SC creates a case to dissipate all energy in the 10 μs, 1000 V DC pulse in the loop resistance!

This leads us to think of using a SC based resistive loop to absorb the surge energy, where SC acts as a switch to turn the loop current on

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*

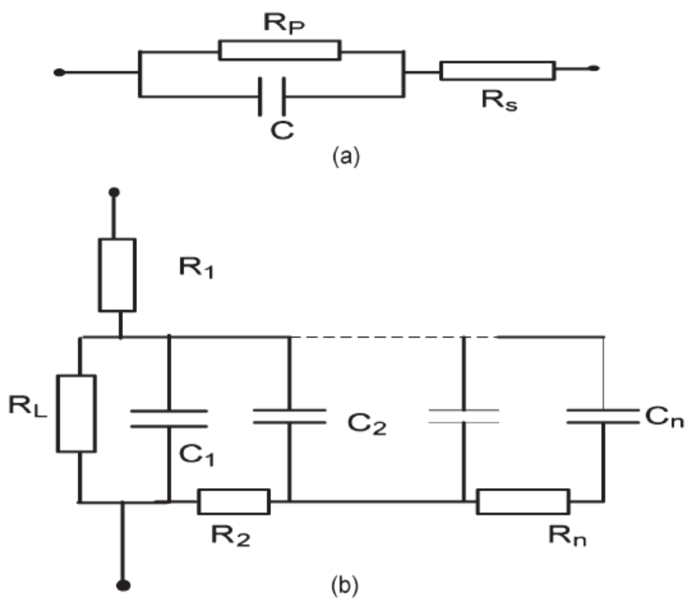


Fig. 2. SC equivalent circuits. (a) Classical equivalent circuit. (b) Ladder circuit.

Supercapacitor circuits have very long time constants

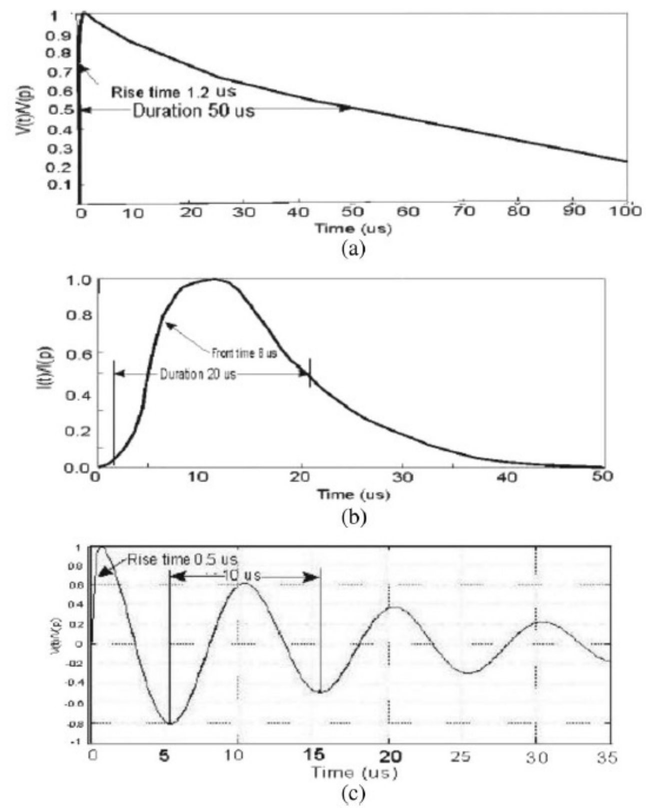
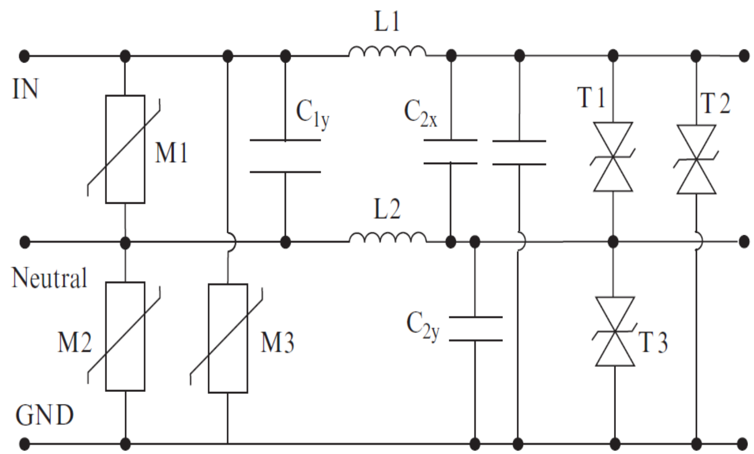


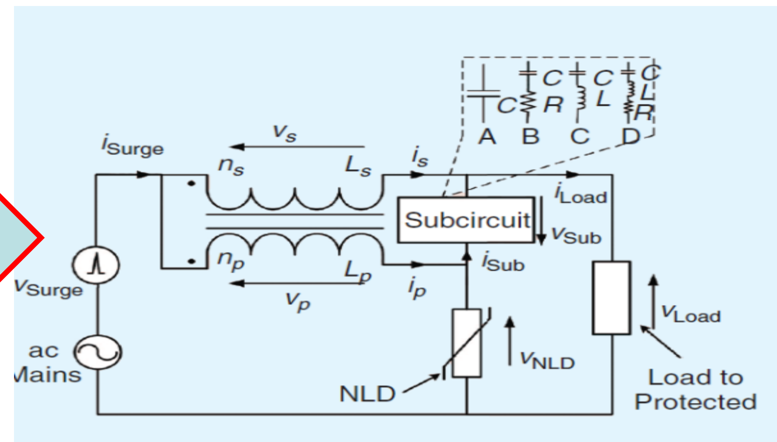
Fig. 3. Few examples of wave shapes defined in surge test standards. (a) Open-circuit voltage waveform. (b) Short-circuit current waveform. (c) Ring wave.

Can we directly replace the MOV/ BBD in a common surge protector by a SC?

- **The answer is no** due to two primary reasons?
  1. If we try to place it between live and neutral, the SC will fail due to its low voltage rating!
  2. Even if we build a very large cap with adequate voltage rating, its AC impedance (1/ 2π *50 * C) will be almost a short circuit!



We had to invent[1,2] a completely new circuit topology to overcome these issues!



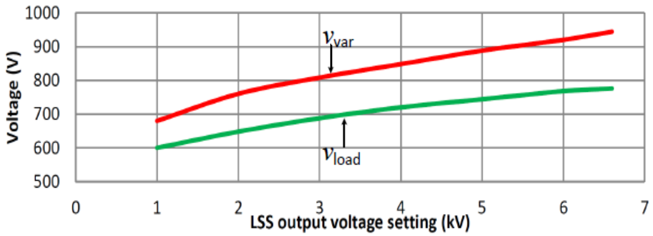
SCASA circuit – SC is placed in the sub-circuit MOV [NLD in figure] is shifted to end of primary coil of the coupled inductor (based on a powdered alloy)

1. **US patent** 9,466,977 B2, **Power and telecommunications surge protection apparatus**, Nihal Kularatna and Jayathu Fernando, Oct 11, 2016
2. **NZ Patent-**604332, **Power and Telecommunication Surge Protection Apparatus**, Nihal Kularatna and Lewis Jayathu Fernando, March 21, 2014

A commercial product based on SCASA

[Courtesy of Thor Technologies, Australia]

- A commercial product was developed in collaboration with Thor Technologies, Australia
- This has lesser components compared to a traditional surge protector
- It satisfies UL 1449 3rd Ed test specification without component deterioration, when repeated surges are applied



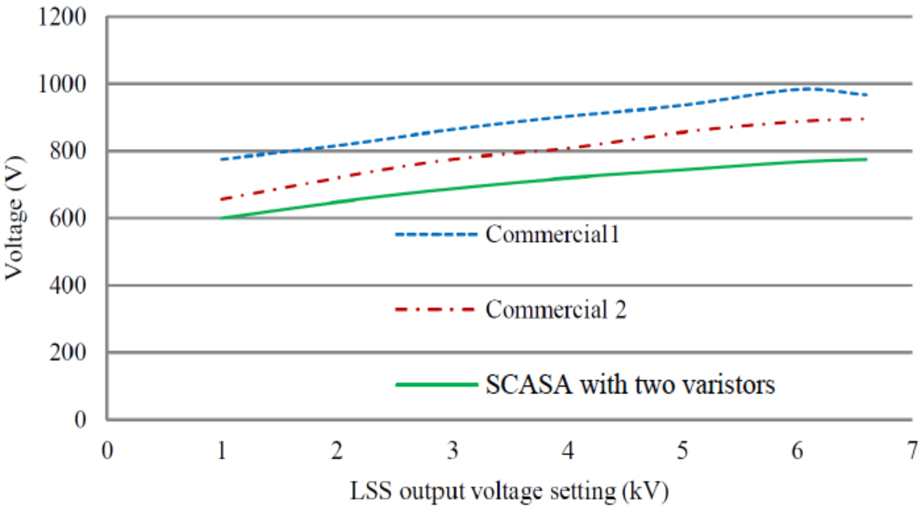


Figure 5.19: Performance comparison of SCASA with two commercial surge protectors

In SCASA[1], number of components are less and the transient related voltage at the protected load is less than the clamping voltage at the MOV

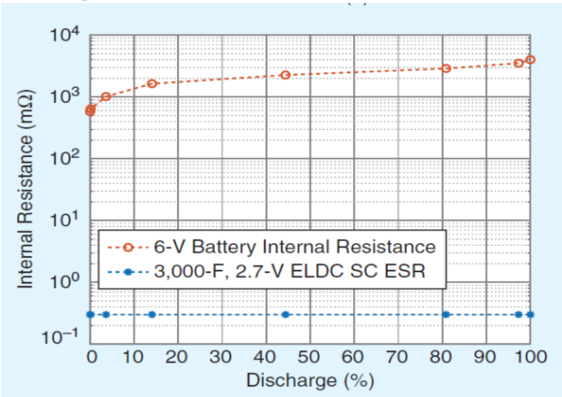
1. Kularatna, N., Steyn-Ross A, Fernando, J. and James, S., ***Design of Transient Protection systems: Including Supercapacitor Based Design Approaches for Surge Protectors***, Elsevier, USA, 2018, 284 pages

Supercapacitor Assisted Temperature Modification Apparatus (SCATMA)

A SC based solution to hot water delay issue

- Supercapacitors have relatively lower ESR values, compared to battery packs.
- ESR does not vary much with the % discharge
- Larger the size of the SC ESR is smaller.
- Maximum power capability of voltage source is given by,
  $V^2/ 4R_{int}$

- A 3000 F, 3.0 V rated (single cell) SC from Samwha has a DC ESR of 0.23 mΩ
- This capacitor could deliver a maximum power of 9.8 kW when fully charged!
- Short circuit current starts at 13,000 amps!
- If you build a series array of ten of them it can theoretically deliver a maximum power of 98 kW!
- However total energy in a single cell will be 3.75 Wh



Comparison of internal resistance: Battery versus SC

These simple calculations lead to case of rapid water heater!

Instant water heating : SCATMA

Well-known problem at water faucets

- In our home environments central water heater is at a distant location from individual faucets
- 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

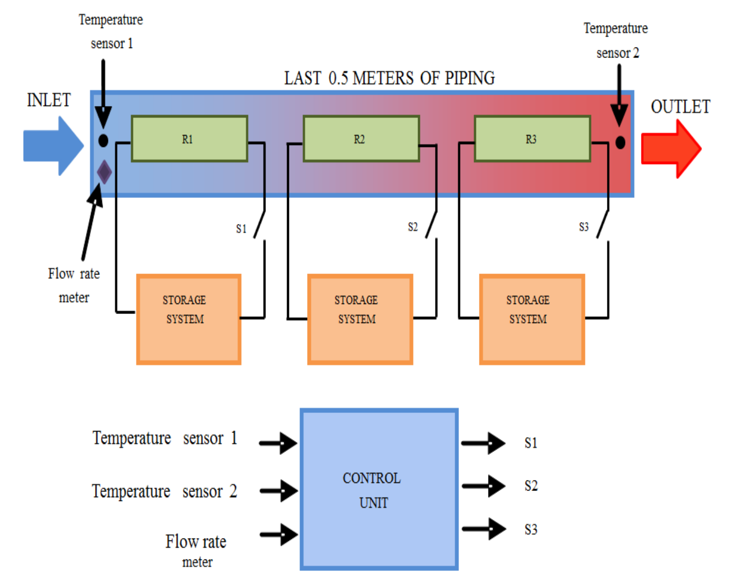
Energy and power requirements for rapid water heating

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

Why it is not easy to solve the problem

- Maximum power we can draw from a wall socket is less than 2.5 kW
- If flowing water is to be heated fast, a 10 to 20 kW heater element is required just before the faucet
- Building heaters and tanks to do this is complex and costly
- Safety/ regulatory issues if 230, 50 Hz mains is to be wired closed to faucet [You need a voltage source lower than 70 V AC/ DC to be safe]

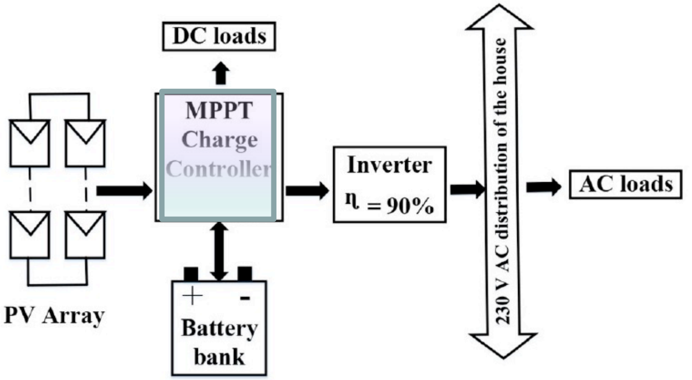
SCATMA



Supercapacitors for DC Microgrid (DCMG) applications

- DCMGs are a rapidly growing new concept for better utilization of renewable energy.
- This is driven by the fact that most electrical products internally operate from DC voltage rails
- Use of battery packs with a maximum power point tracking (MPPT) charger/ controller is very common in traditional solar powered systems coupled to the AC grid supply.
- With SC modules could be build with hybrid or capa-battery type SC cells, we gradually see the possibility of using SCM in place of battery packs
- One major issue faced in replacing a battery bank with a SCM is the MPPT implementation
- All MPPT techniques, try to match the internal resistance of a solar panel to the input resistance of the (battery+ load) and the controller.
- A SCM for energy storage means a capacitive load ….
- Matching impedances is a theoretical issue!

Another SC assisted (SCA) technique set can solve this issue.



Is there a common theoretical concepts behind all these SCA techniques?

Answer is a **BIG YES… a unique extension to our text book R-C circuit theory**

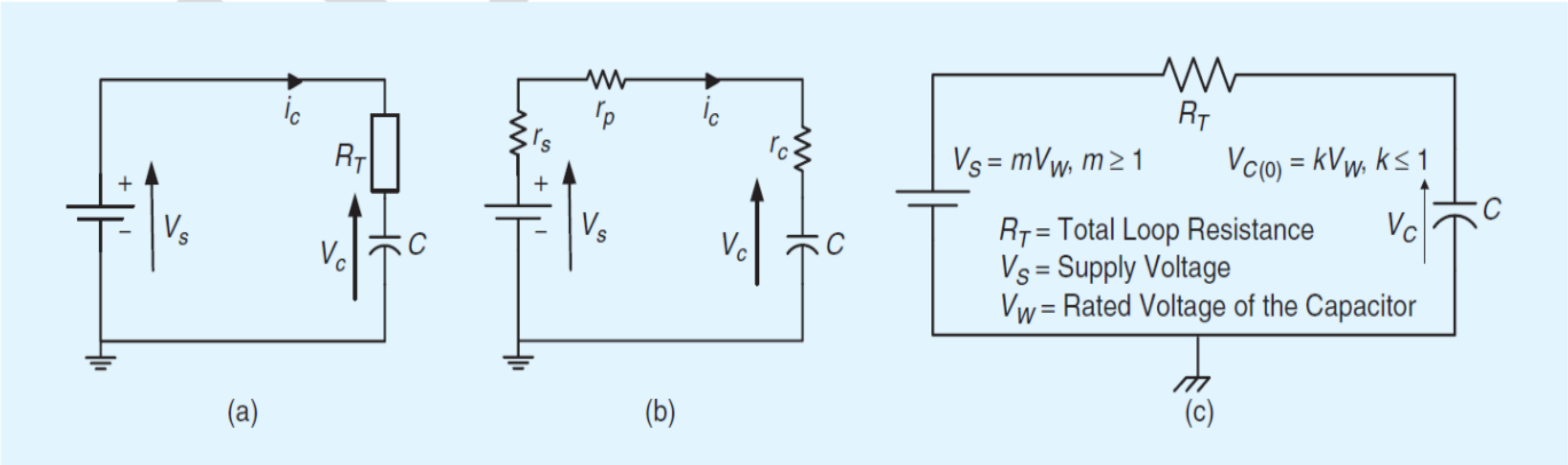


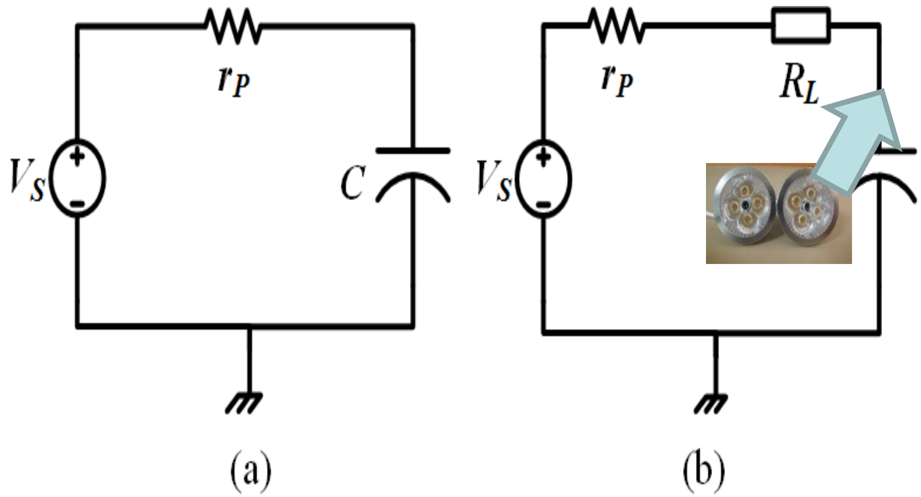
Figure 3 – The generalized case of the R–C circuit. The (a) simple textbook case with a capacitor starting from zero voltage, (b) resistive components contributing to loop resistance (R_T), and (c) the SC in a precharged condition.

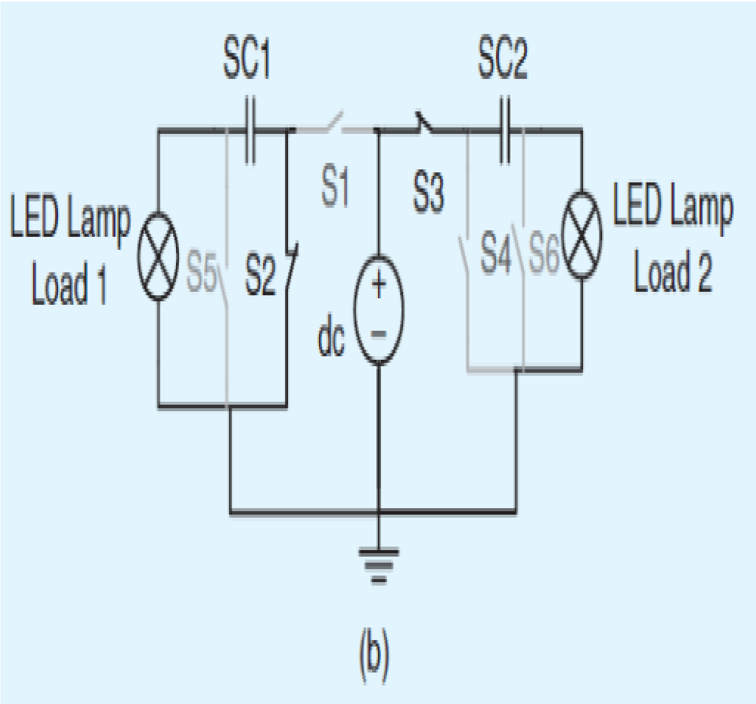
- It is based on two simple concepts
  - In the simple RC circuit replace the capacitor with a supercapacitor..[Extend time constant]
  - Add a useful resistive load, a heater, DC-DC converter, inverter or any power electronic building block (PEBB) [To consume losses in resistor of RC circuit]

Then by modifying the power source by a *factor m* and keeping the capacitor pre-charged with *factor k* (as in Figure 3(c)), you achieve SCA- Loss management theory

SC assisted LED lighting for DC microgrid and renewable energy systems

SCALED Technique[1]





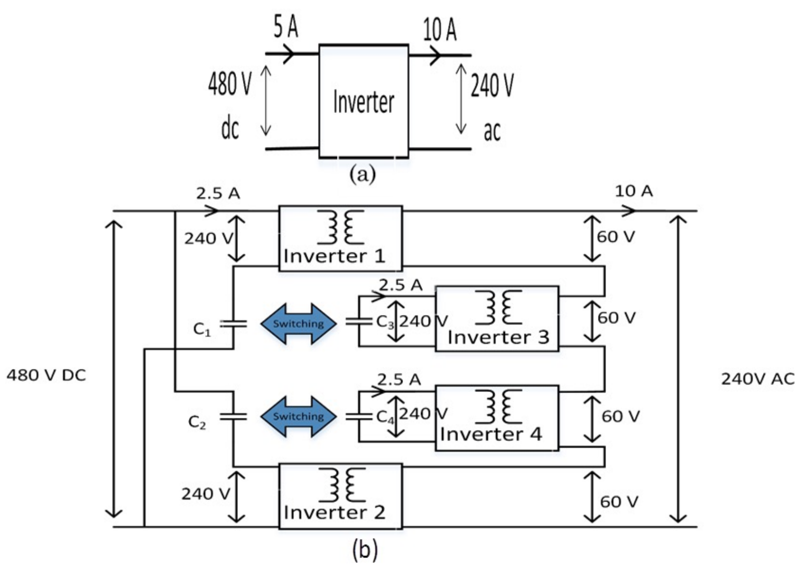
- LED lighting is internally operating with a DC supply
- DC products are more attractive for DCMG systems
- SC banks could replace battery banks, for environmentally friendly systems
- MPPT systems for battery banks will not work with SC banks (Impedance matching not possible)
- SCALED systems were developed to rescue this theoretical issue
- In SCALoM concept, we use a DC operable LED lamp load as the PEBB

Implementation of SCALED system using two 12 V DC LED banks from a photovoltaic source

1. D. Jayananda ;N. Kularatna ; D.A. Steyn-Ross, Supercapacitor-assisted LED (SCALED) technique for renewable energy systems: a very low frequency design approach with short-term DC-UPS capability eliminating battery banks, IET Renewable Power Generation, Vol. 14 Iss. 9, pp. 1559-1570

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 SCM and a useful resistor (inverter) to circumvent losses**
- **This technique can also be used to extend the input range of inverters useful in renewable energy systems[1]**

1. Gunawardane, K., Bandara, N., Subasinghage, K. & Kularatna, N., Extending the input voltage range of solar PV inverters with supercapacitor energy circulation, Electronics- MDPI, Vol 10, 88, 17 pages

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
  - Building high efficiency very low frequency DC-DC converters
  - Developing 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 make us of commercial EDLCs in many more applications and much more versatile than in simple energy storage systems….

Thank you…

5th May 2020