Supercapacitor applications for renewable energy systems and DC microgrids

Nihal Kularatna
Associate Professor In Electronic Engineering
School of Engineering
The University of Waikato
Hamilton
New Zealand

Presentation outline

- An introduction to supercapacitors / Ragone plot
- Different types of commercial supercapacitor and their properties
- Discharge characteristics of different types
- Renewable energy systems and DC Microgrids
- Need for different types of converters
- Few examples of non-traditional SC applications for renewable energy and DCMG areas
- Future possibilities
- Conclusion

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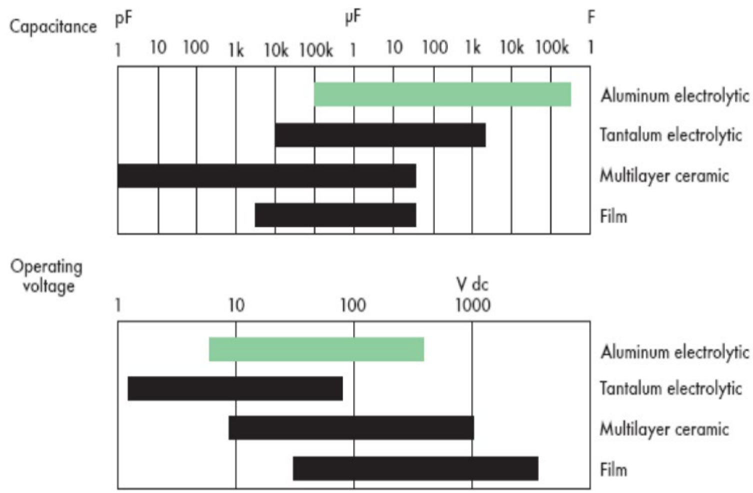
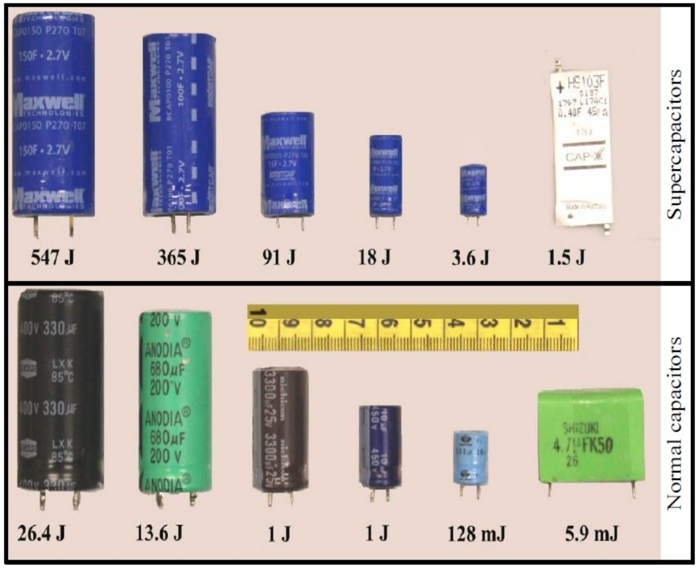
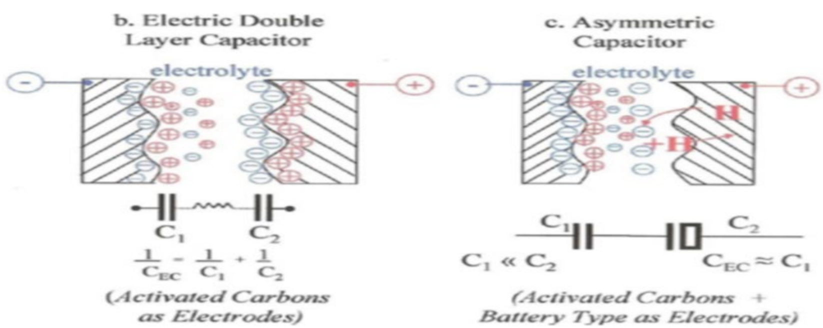
Normal capacitors and their limits

Physical Comparison of Supercapacitors (SC) and Electrolytic Capacitors



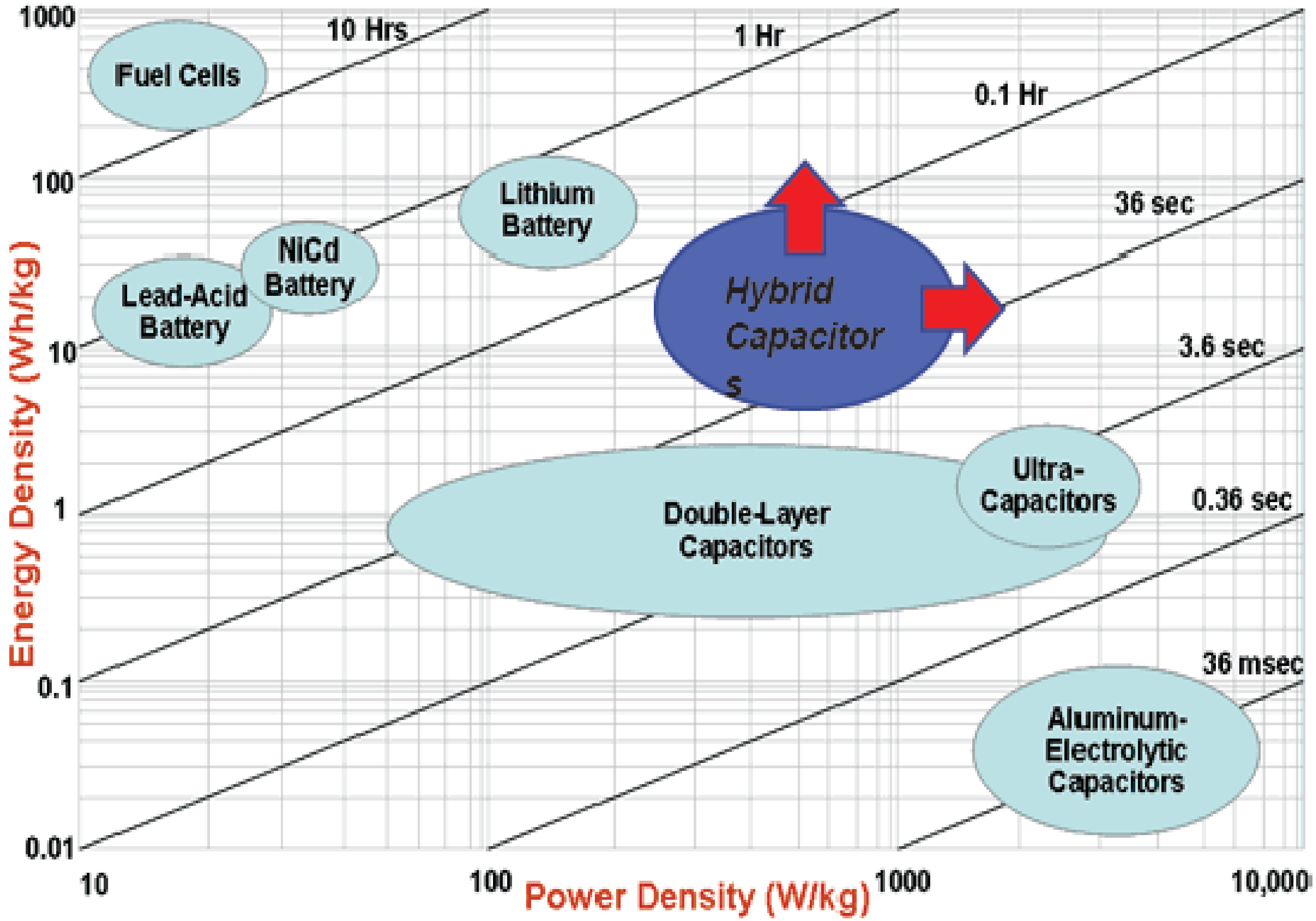
2. Common dielectric materials, i.e., aluminum oxide, tantalum tetroxide, titanium oxide barium, and polyester polypropylene, also pose limits on capacitance level and operating-voltage capabilities.





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

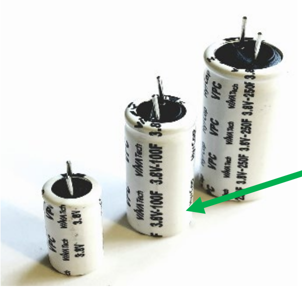
- There are few basic types
  - Symmetrical double layer capacitors
  - Hybrid types with one battery type electrode
  - Capa-batteries
  - Lithium SCs

Sources : Samwha Electric

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

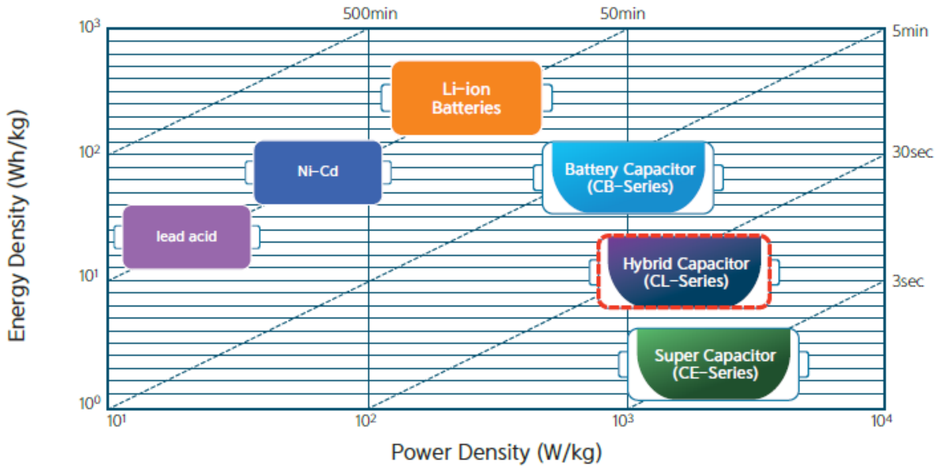
Then hybrid devices with one electrode similar to Li-ion batteries were commercialized ***[8.2Wh energy capability example]***

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



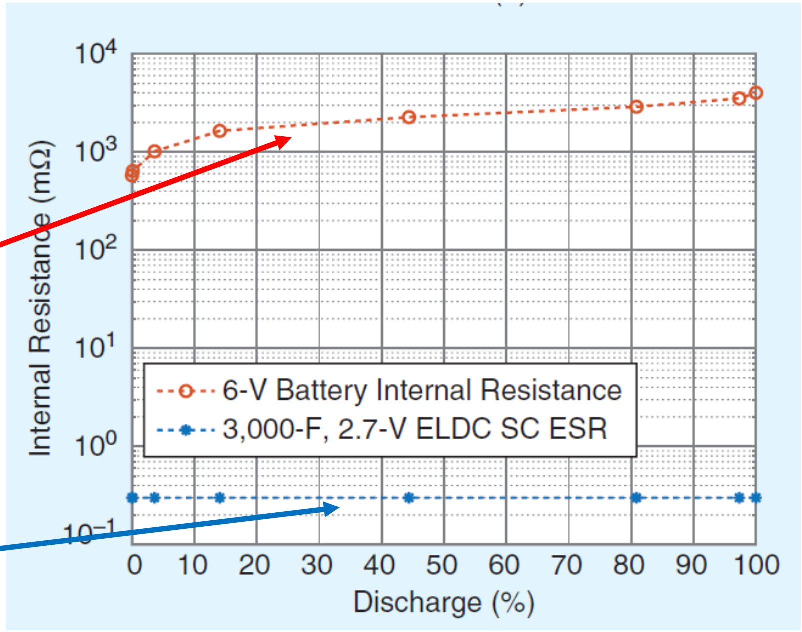
Lithium supercapacitors [Source: Vinatech]

Battery versus SC



Source: Samwha electric

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



Comparison of internal resistance: Battery versus SC

In a battery internal resistance increases with % discharge

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

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	-40^0C to + 60^0C	-20^0C to + 40^0C	-20^0C to + 50^0C	-10^0C to + 50^0C
Charge-Discharge efficiency	≈100%	≈100%	≈90 -100%	70% -85 %
Cycle life	Over 500,000	Over 50,000	Over 20,000	1000-1500

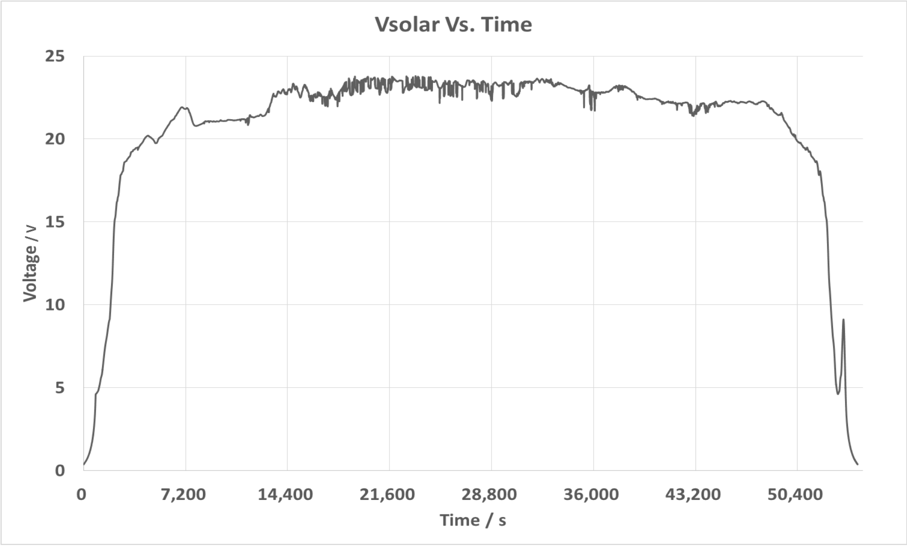
Given the case of high cycle life compared to li-ion batteries sC based energy storage systems are more effective on a longer-term perspective, and they can be considered fit and forget devices, and better tolerance for freezing temperatures

Renewable energy systems and Applications of Supercapacitors

A summary of renewable energy sources such as solar and wind energy systems

- **They generate DC outputs**
- **They are unstable in power output**
- **Need energy buffers or need to be work in combination with the legacy AC grid**
- **Traditional systems are based on battery packs which are limited in life and the comes with disposal issues**

Instability of renewable sources – An example of solar irradiance over a 24 hour period



Different types of PV systems

- In a traditional PV systems an MPPT charge controller, battery pack and the inverter systems are linked to existing AC supply

- In a world of DC powered appliances we can totally remove the inverter and hence reduce some of the associated loses in the energy supply

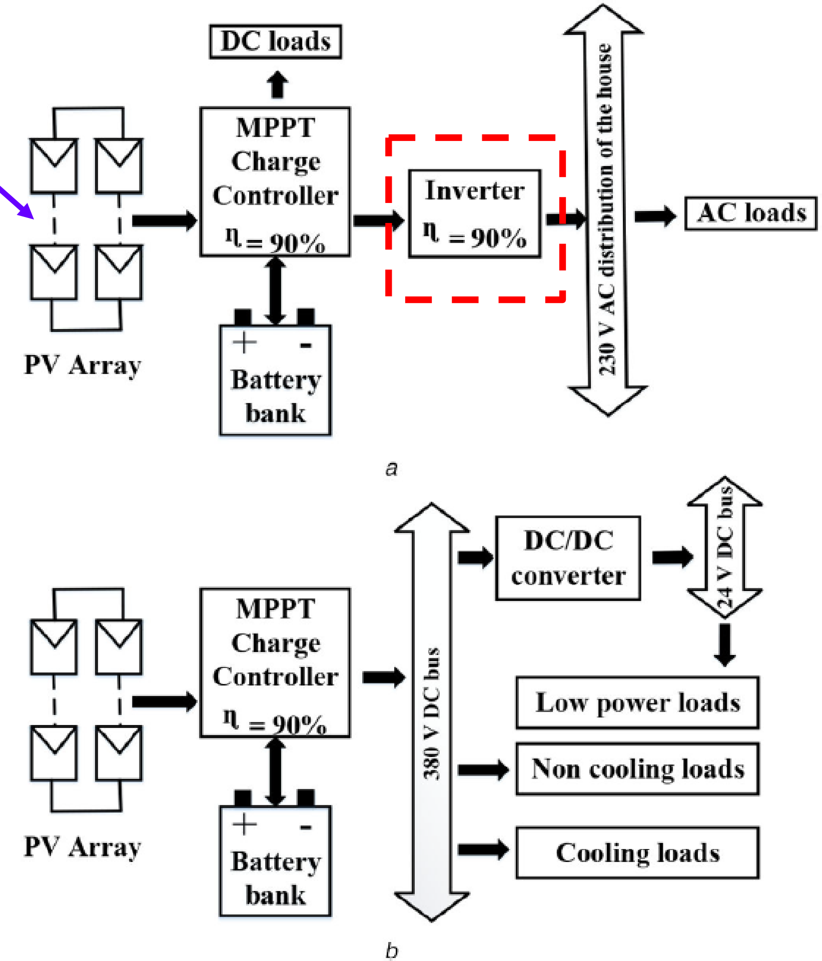
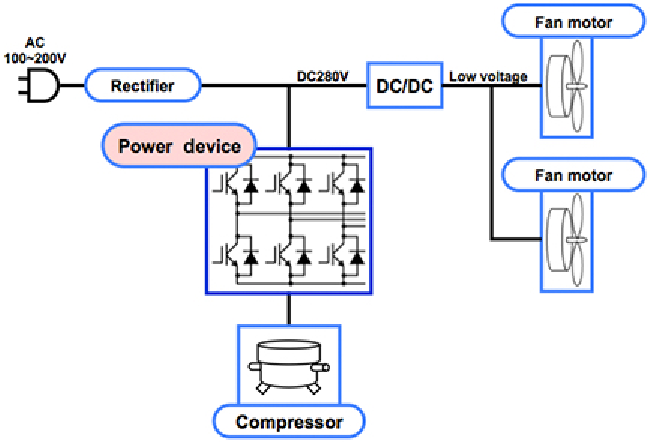


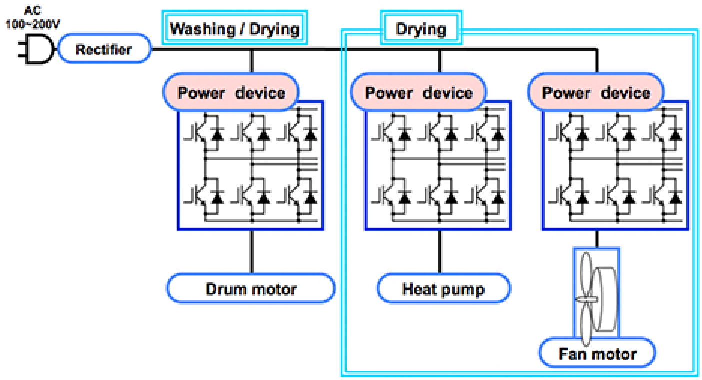
Fig. 2 *Existing PV system*
(a) Typical grid-connected PV system, *(b)* Typical off-grid PV system [8]

Commercial Inverter Driven White Goods

- Most latest white goods are internally DC bus based
- They are marketed as "inverter-driven" products



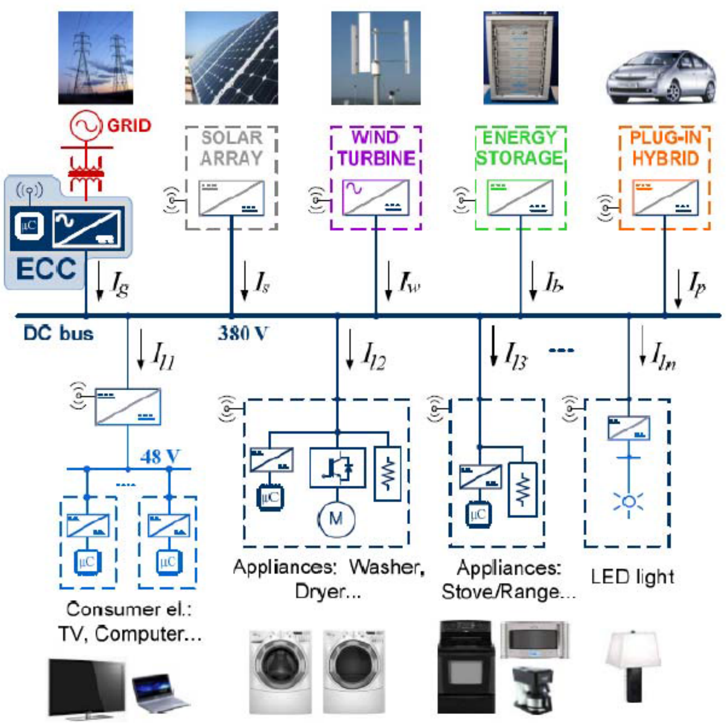
Refrigerator



Washer-dryer combinations

If we can supply DC to the internal DC bus of these appliances one lossey stage is removed.

Energy Storage in the Nano/Microgrid Development Scenario



1. DC-based nanogrid system in a future home.

Data centre powering with DC

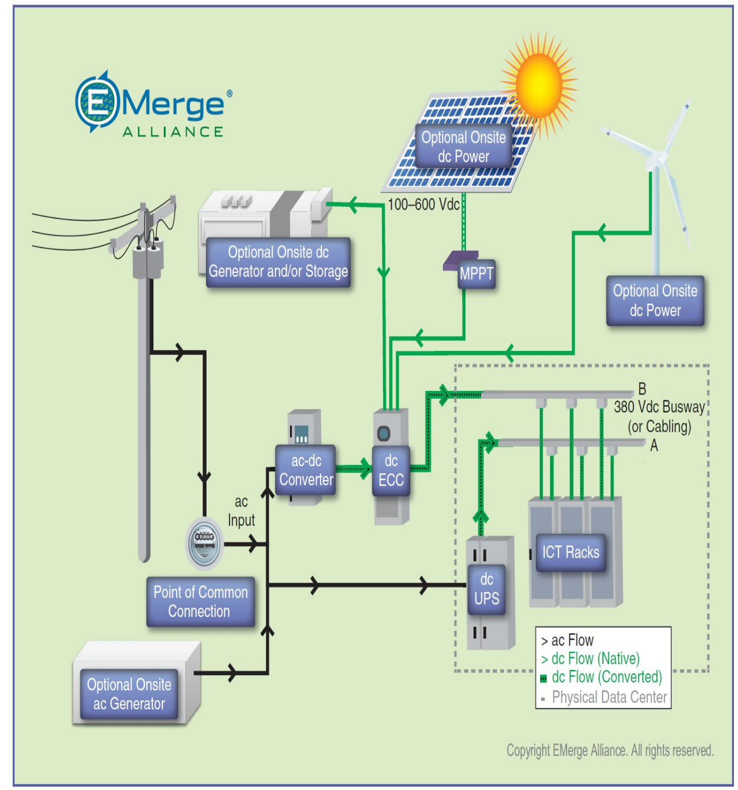
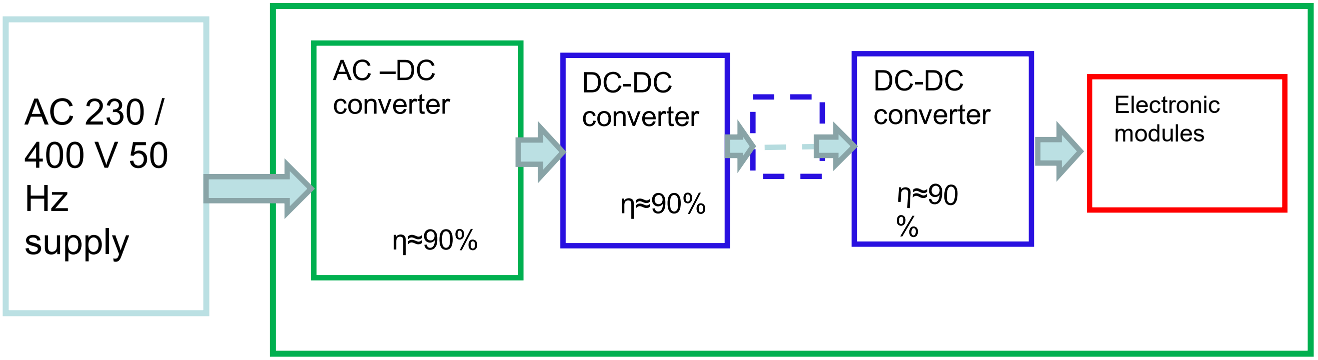


figure 6. Pictogram of EA's dc standards as implemented in a data center.

Source Credit: Patterson, B., DC, Come Home, IEEE Power and Energy Magazine, Nov-Dec 2012, pp 60-69

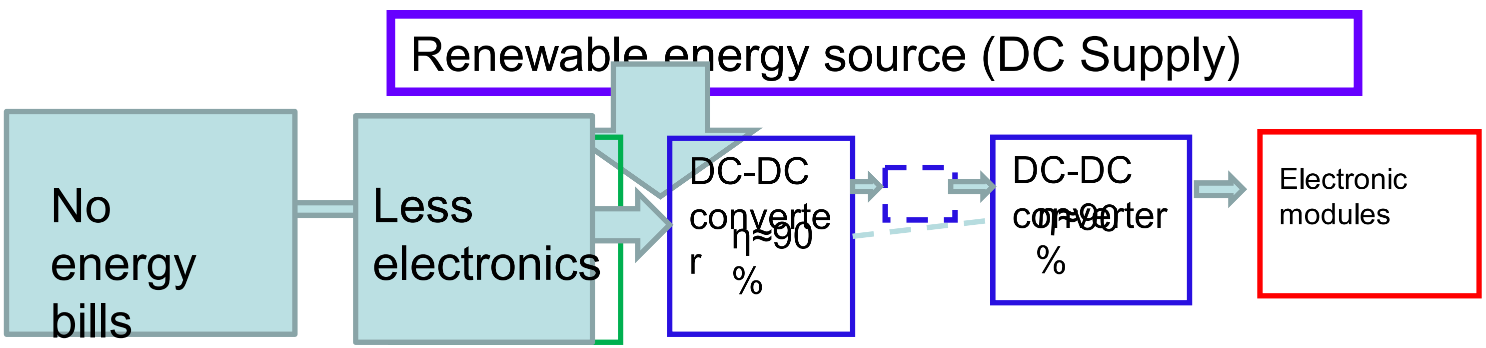
Energy Efficiency and Power Converters- As applied to consumer and industrial electronics



Energy flow within a typical electronic product or a system

- Powering electronic modules with high end to end efficiency (ETEE) is a well known issue in power electronics industry
- If you have three cascaded converters of 90% efficiency each ETEE will be 73% (=.9x.9x.9)

Direct DC input could remove the rectifier stage and save efficiency and reduce costs



DC Microgrid concept: No energy bills; Lower product costs; save environment

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.

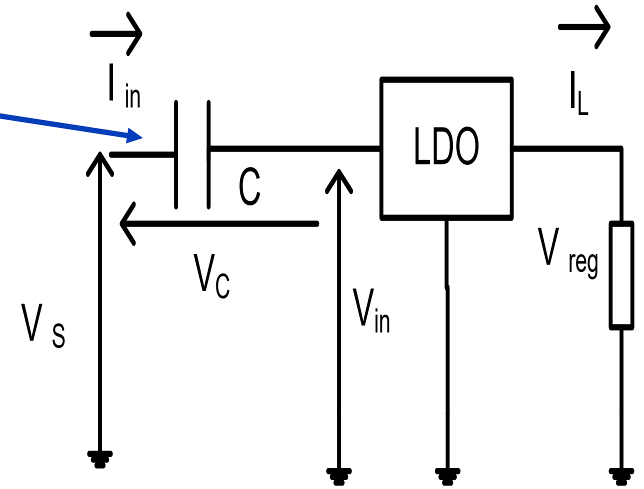
These can be used in power converters and protection systems useful in renewable energy applications.

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

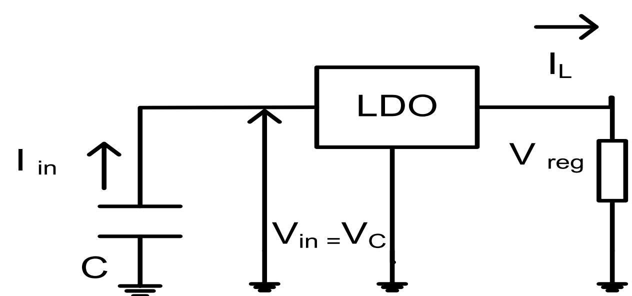
Now let us insert a SC pre-charged to Vc in the series path …



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

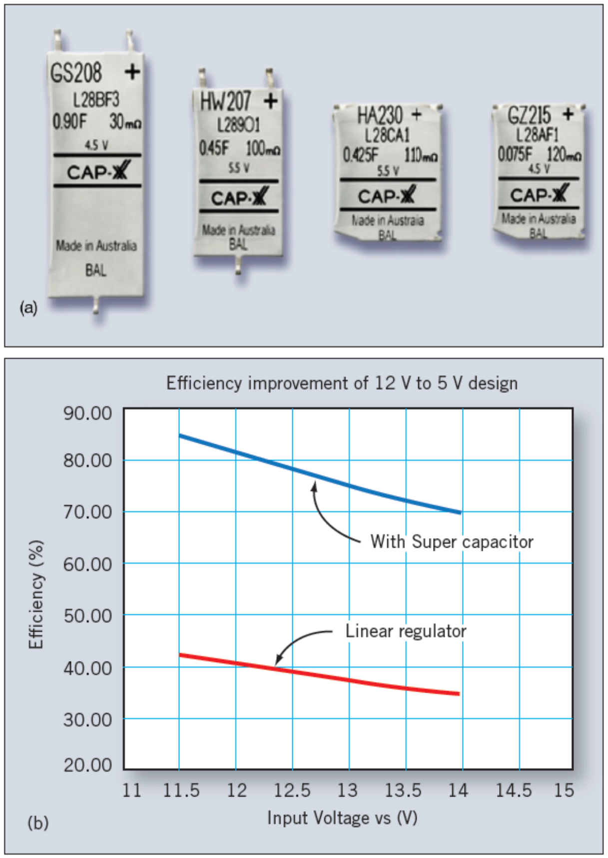


Fig. 3(a) Capacitor size reductions in an early prototype for 12-5V regulator super-caps used. (b) Shows efficiency improvements in 12-5 V regulator supercaps.

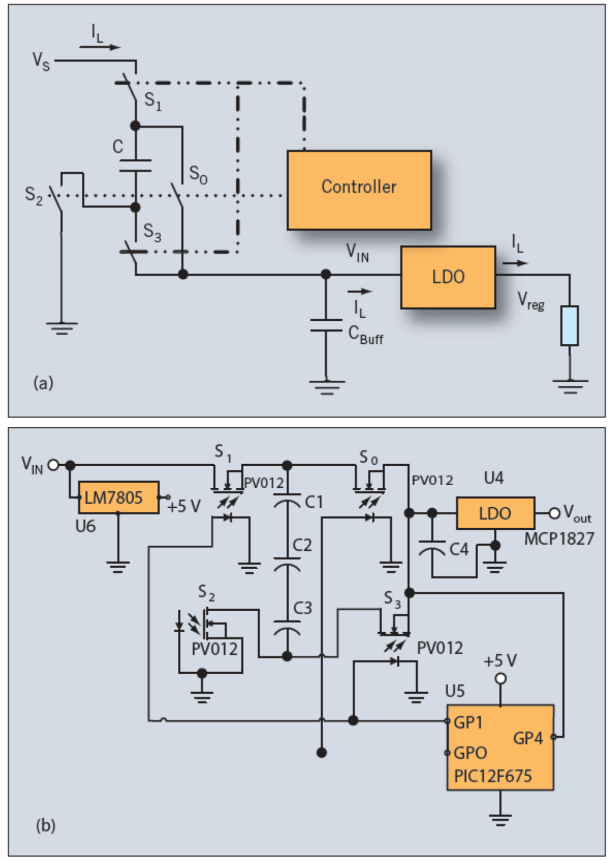
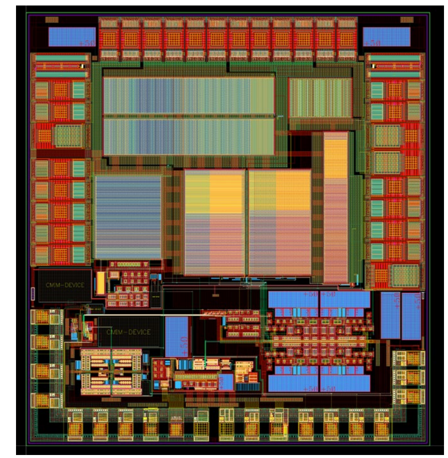


Fig. 4(a) The 12 V to 5V circuit to achieve efficiency improvements shown in Fig. 4(b). The implementation in Fig. 4(b) is shown using a PIC microcontroller.



SCALDO technique in IC implementation

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

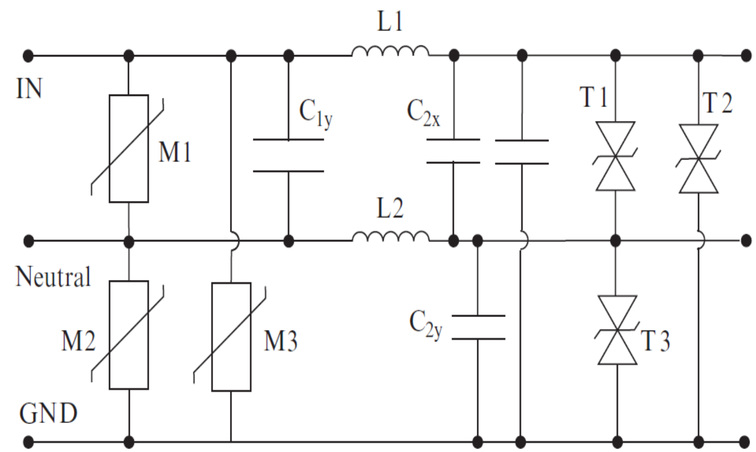
Ref: (2014) Kankanamge, K., Kularatna, N., Improving the end-to-end efficiency of DC-DC converters based on a supercapacitor assisted low dropout regulators (SCALDO) technique, IEEE Transactions on Industrial Electronics, Vol 61, Iss 1, January 2014, pp 223-230

Supercapcitor based techniques for transient surge absorbers

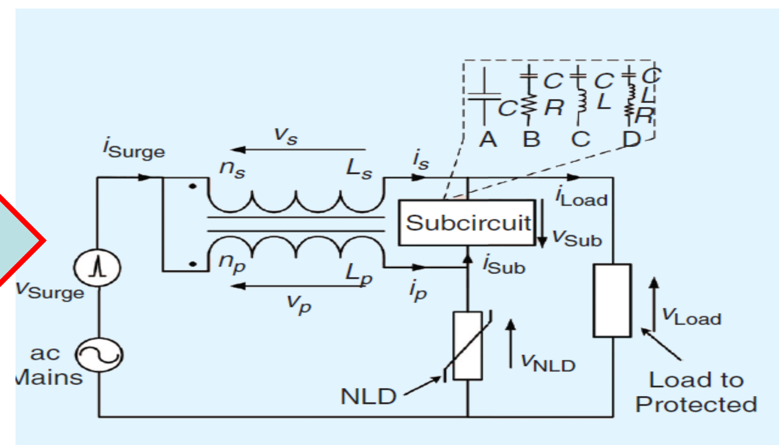
SC Assisted Surge Absorber (SCASA) Technique

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!



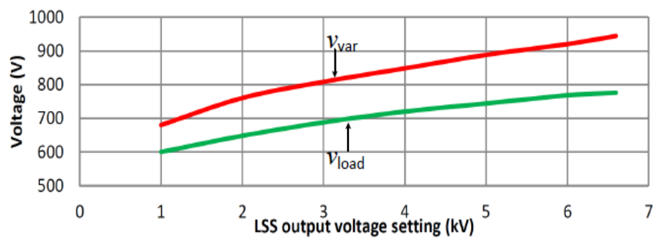
SCASA circuit – SC is placed in the sub-circuit MOV [NLD in figure] is shifted to end of primary coil of the coupled inductor (based on a powdered alloy)

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



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

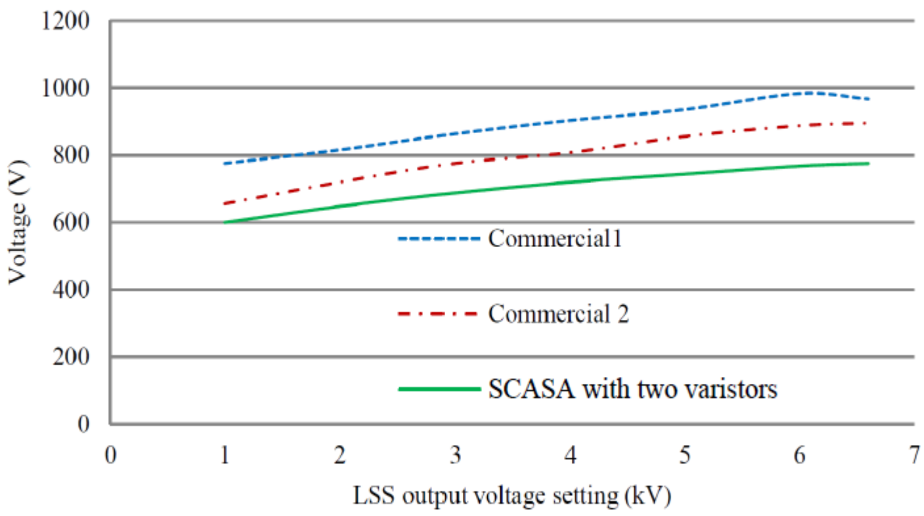


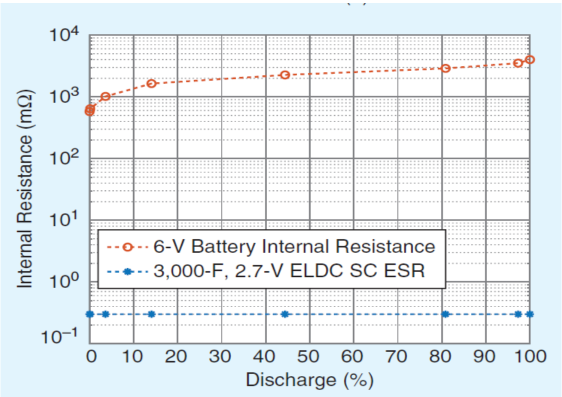
Figure 5.19: Performance comparison of SCASA with two commercial surge protectors

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,
  $V^2/ 4R_{int}$



Comparison of internal resistance: Battery versus SC

- 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

These simple calculations lead to case of rapid water heater!

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**

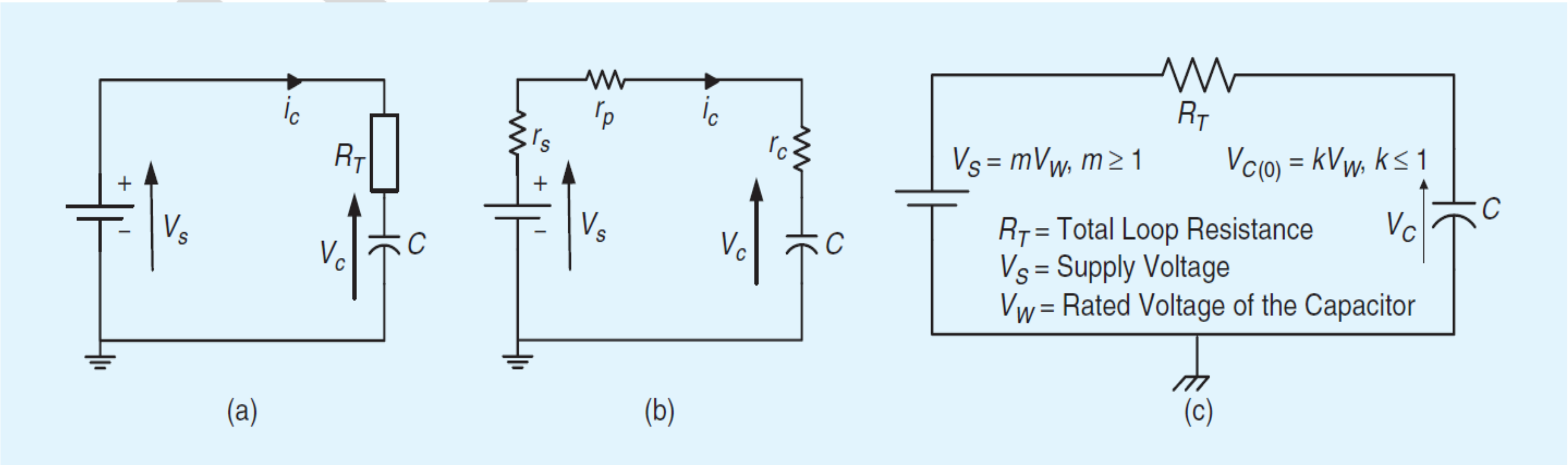


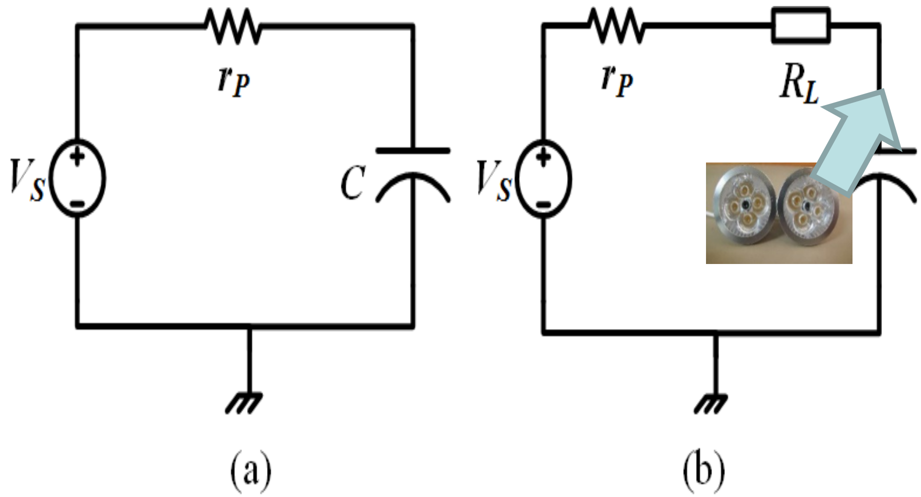
Figure 3 – The generalized case of the R–C circuit. The (a) simple textbook case with a capacitor starting from zero voltage, (b) resistive components contributing to loop resistance (R_T), and (c) the SC in a precharged condition.

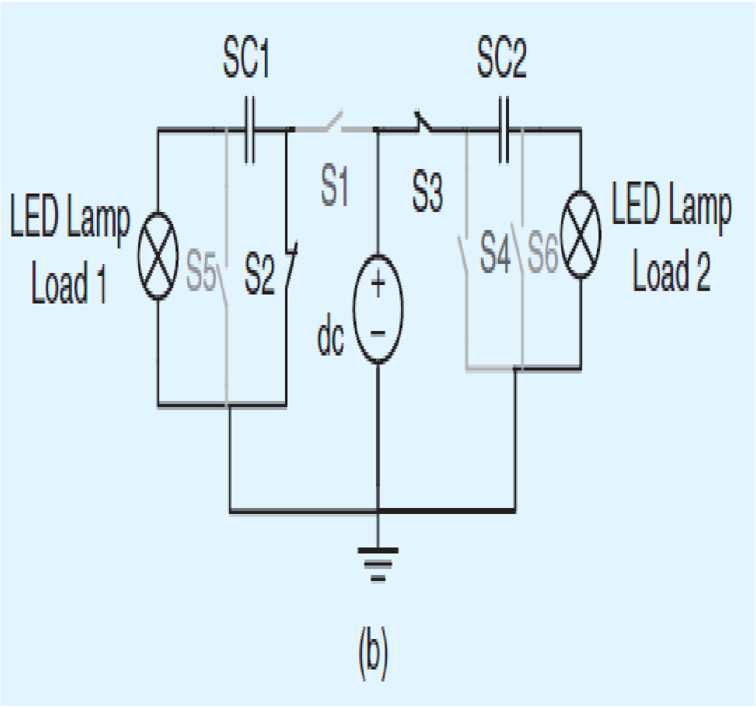
- It is based on two simple concepts
  - In the simple RC circuit replace the capacitor with a supercapacitor..[Extend time constant]
  - Add a useful resistive load, a heater, DC-DC converter, inverter or any power electronic building block (PEBB) [To consume losses in resistor of RC circuit]

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]





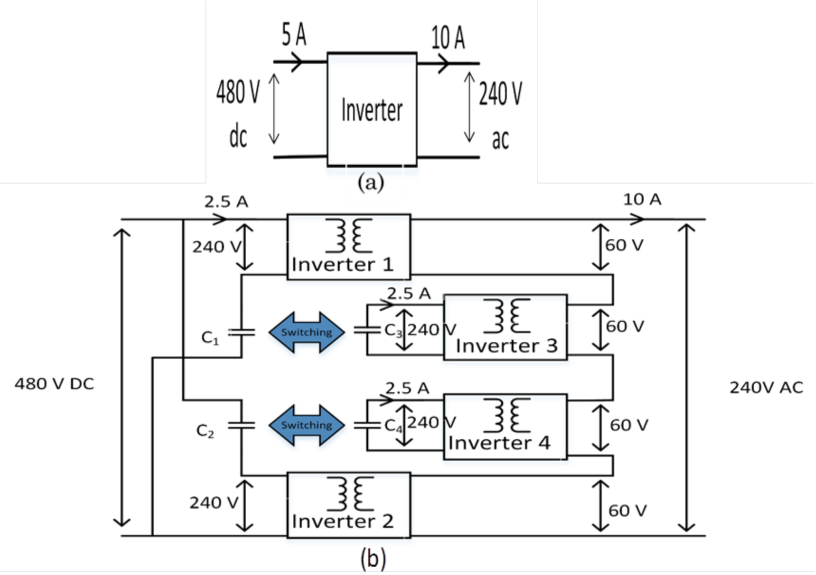
- LED lighting is internally operating with a DC supply
- DC products are more attractive for DCMG systems
- SC banks could replace battery banks, for environmentally friendly systems
- MPPT systems for battery banks will not work with SC banks (Impedance matching not possible)
- SCALED systems were 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