# Benefits of Million Times Larger Capacitance in EDLCs: Supercapacitor Assisted Novel Circuit Topologies

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# Presentation outline

- Designer's view point on supercapacitors with a summary on traditional applications
- Non traditional supercapacitor applications – **Supercapacitor Assisted (SCA) techniques**
- High efficiency linear DC-DC converters at extra low frequencies **-[ SCALDO technique]**
- Supercapacitor based high performance surge absorbers- **[ SCASA technique]**
- Supercapacitor based rapid water heaters – **[ SCATMA technique]**
- SC energy storage for DC microgrid applications – **[SCALED technique]**
- SC assisted high density inverters - **[ SCAHDI technique]**
- How simple resistor-capacitor charging loop theory is extended in SCA techniques – **[SCALoM theory]**
- Conclusion

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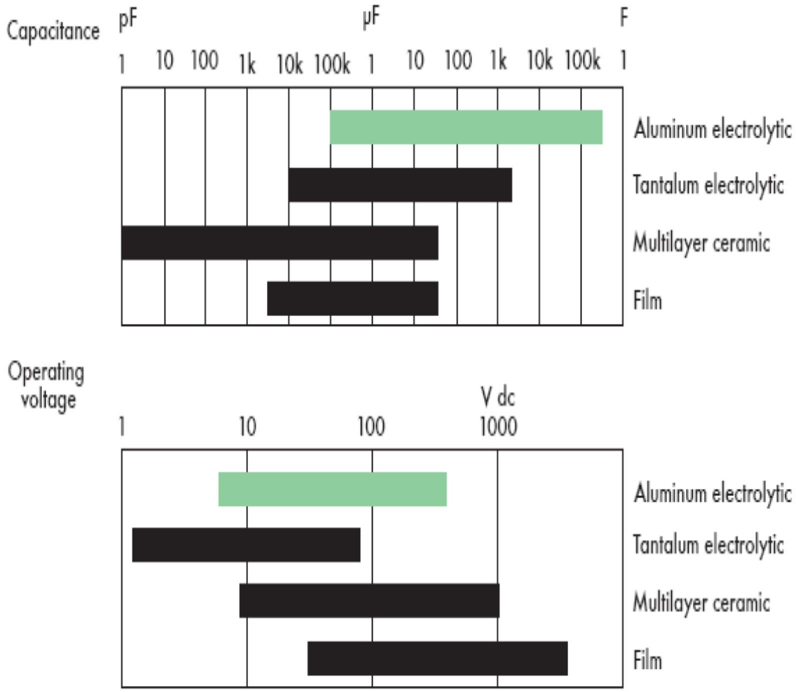
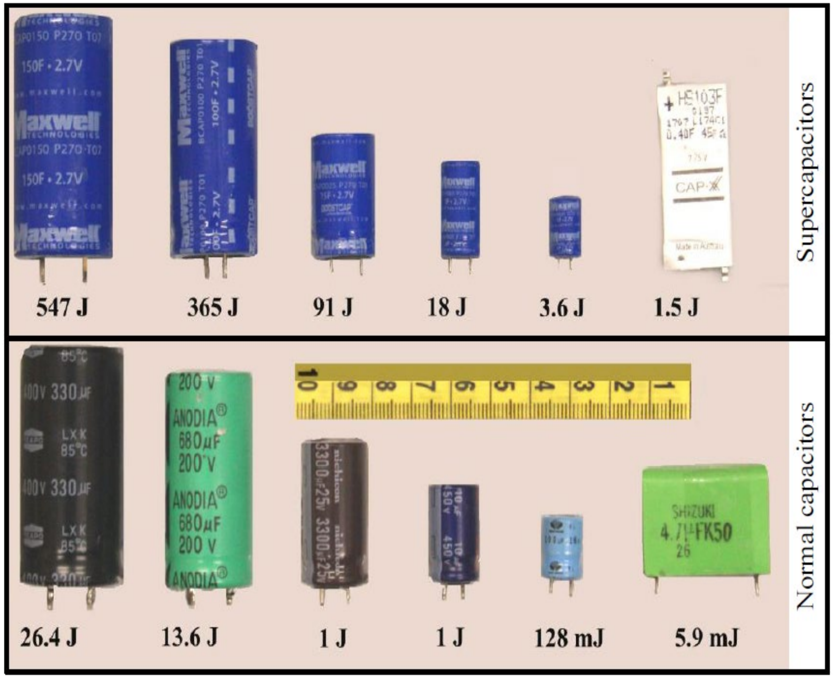
# Normal capacitors and their limits




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.

Source: Dirjish,.M., Ultracapacitors branch out to wider markets, Electronic Design , On line ed, Nov 17, 2008

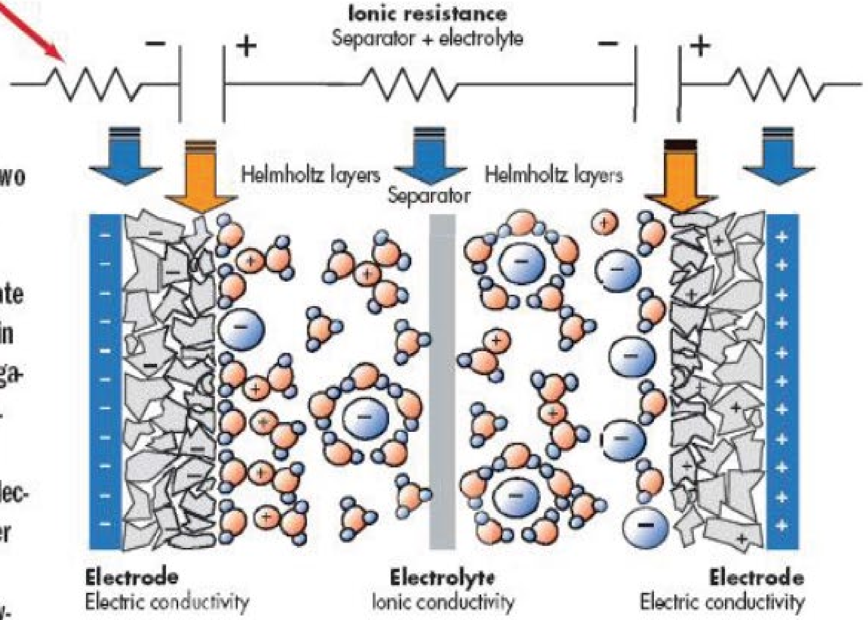
# Physical Comparison of Supercapacitors (SC) and Electrolytic Capacitors




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

# SC is an electric double layer device

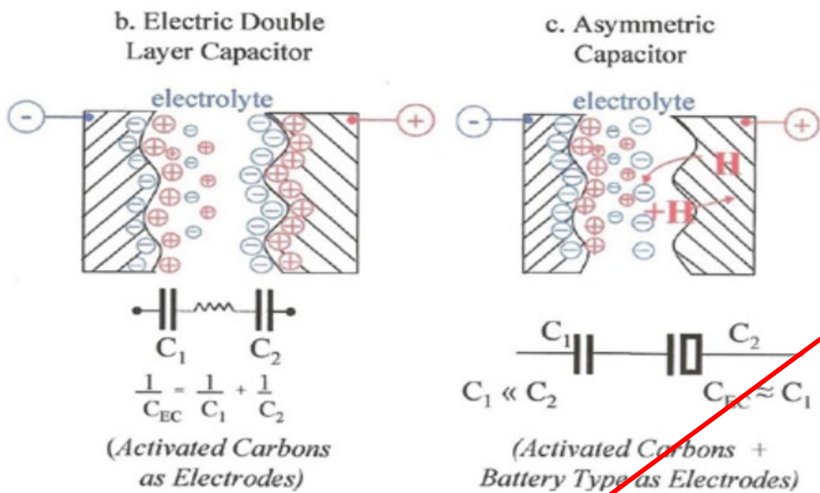
- Inside a SC two capacitors are formed in series




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.

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

# Supercapacitors versus Hybrid Supercapacitors





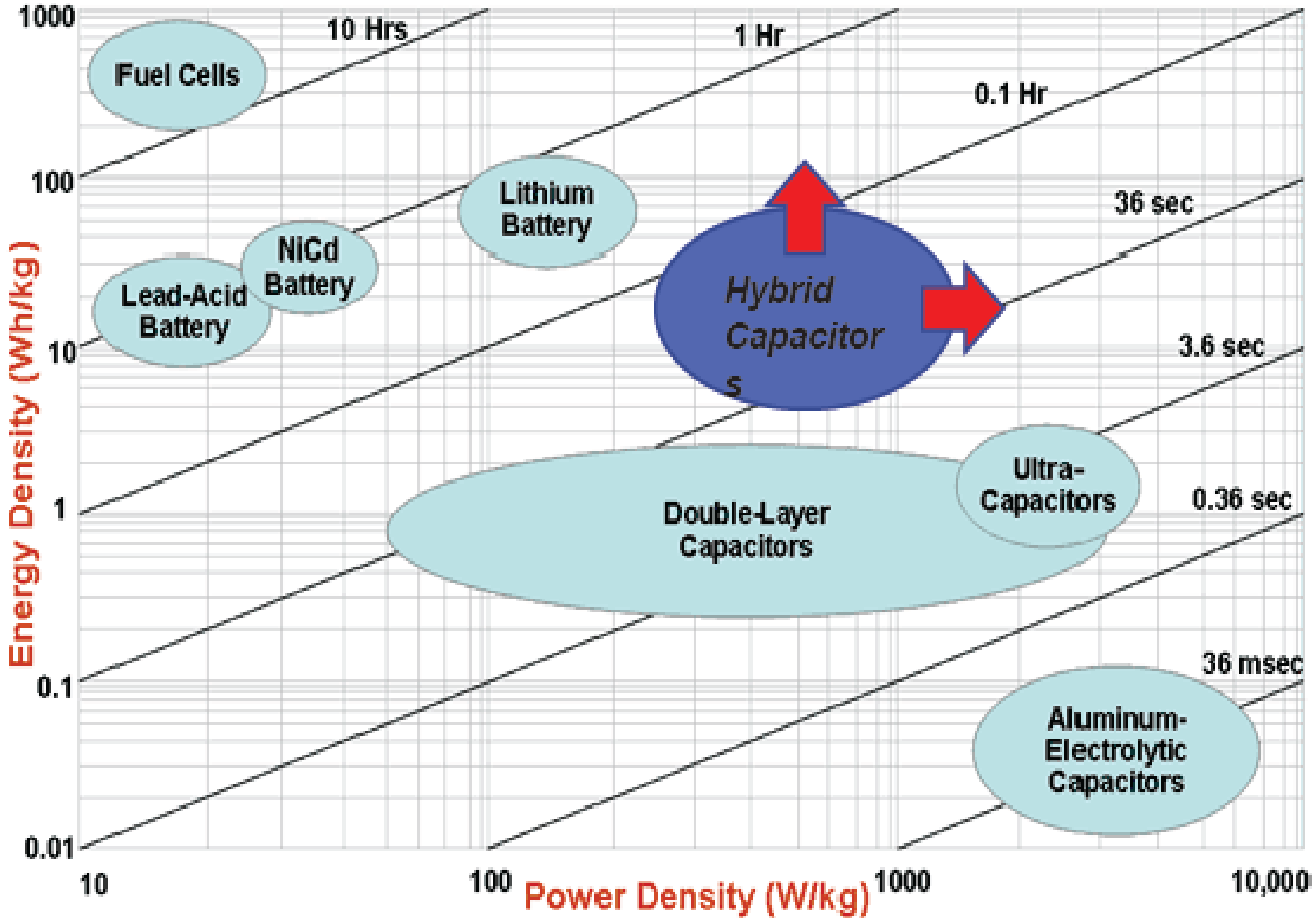
Source : Samwha Electric

- 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 ]***

# Ragone plot




Source US Defence Logistics Agency

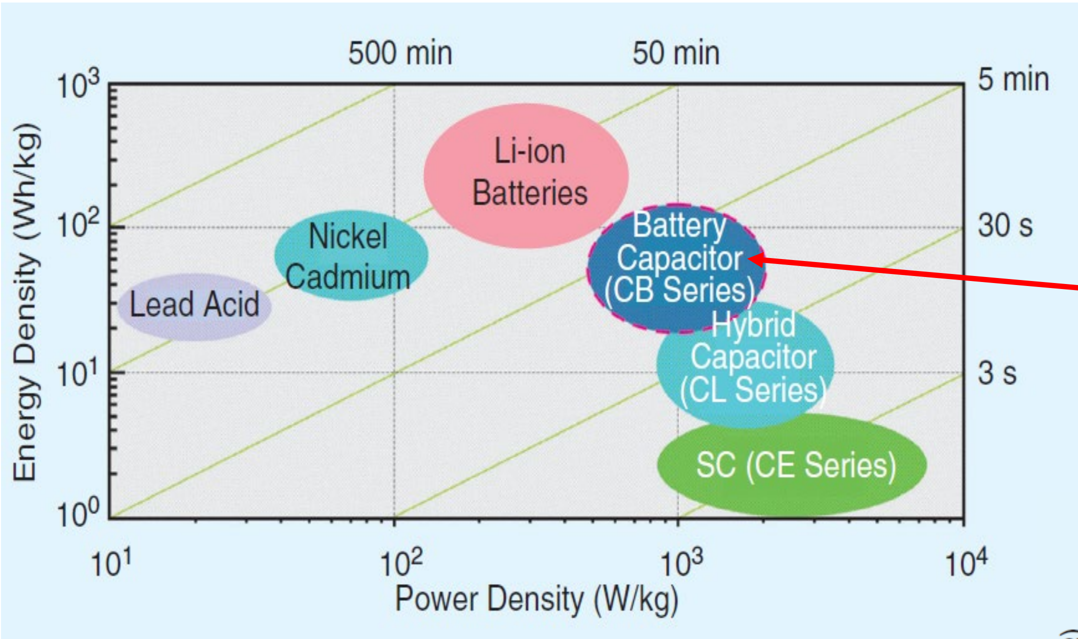
# Comparison of practical devices

| 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 |

# A broad comparison – Key specifications based

| | Power Density | Energy Density | Cycle life | Temperature range |
|---|---|---|---|---|
| Li-ion battery | 3 kW/kg | 200 wh/kg | 500-1000 | $0^{o}$C- $60^{o}$ C |
| Symmetrical SC | 10 kW/kg | 10 Wh/kg | 500,000 to 1,000,000 | - $40^{o}$C- $60^{o}$ C |
| Hybrid SC | 5kW/ kg | 25 Wh/kg | 10,000 - 50,000 | -$20^{o}$C- $60^{o}$ C |

# Battery versus SC

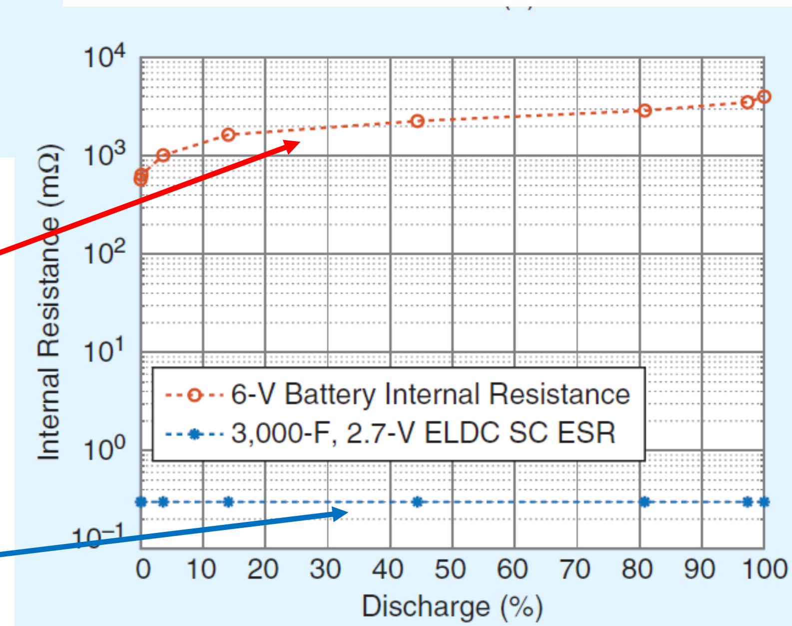



- Capa-batteries gradually reach the energy density of lead-acid batteries

**Source : Samwha Electric**

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

# 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

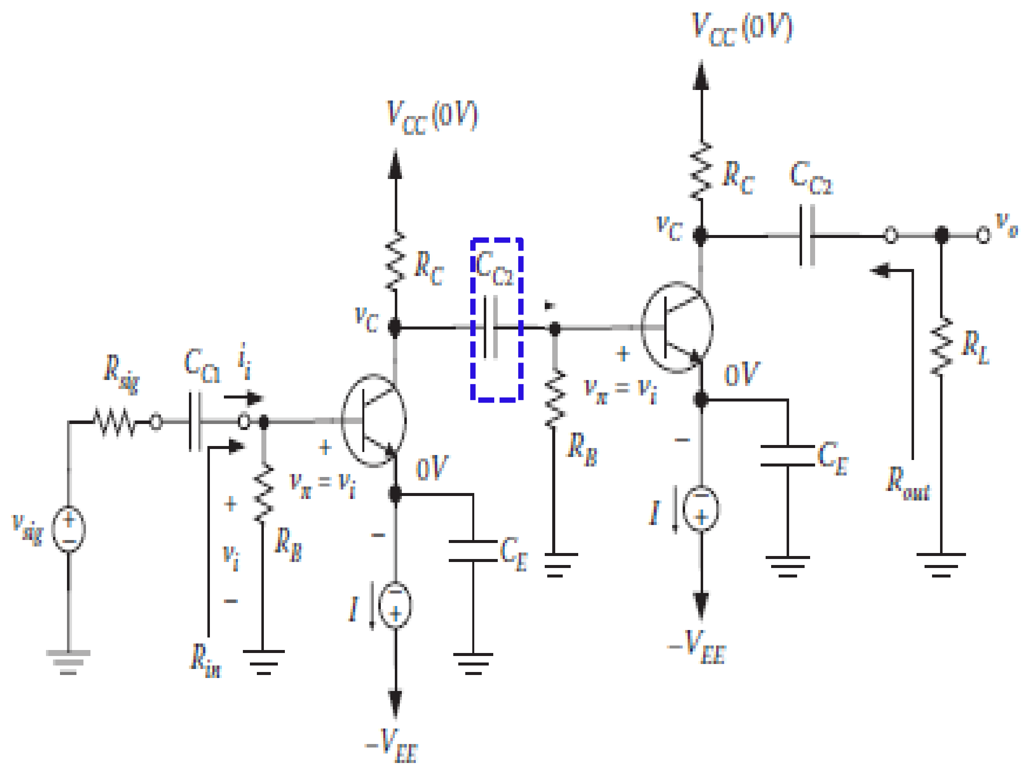
- In many of these applications battery-supercapacitor hybrid systems are used

*Non traditional applications of supercapacitors*

# Supercapacitor Assisted (SCA) Techniques

# Capacitors in simple DC blocking circuits

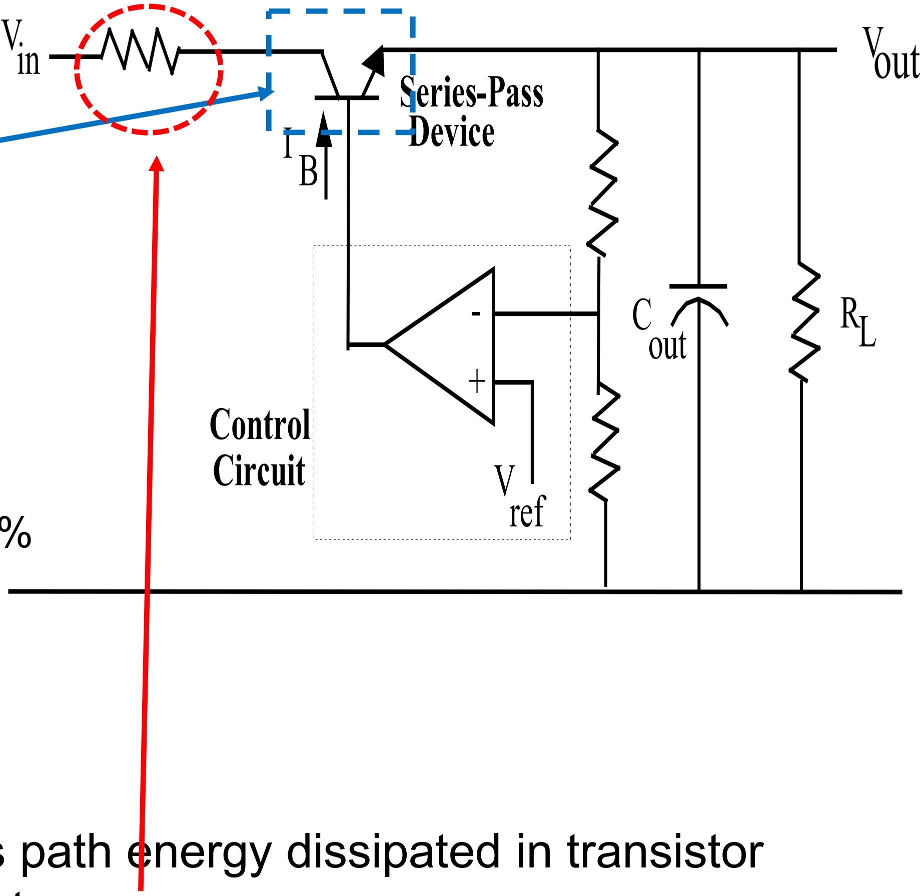
- We use electrolytics and ceramics as DC blocking elements
- Typical values used are from fe nano-farads to tens of microfarads
- When a circuit is powered, blocking capacitor charges to t difference in voltages within micro to millisecond time perio
- If we replace a 1 μF capacitor with a 1 F capacitor the circuit take one million times longer to reach its steady state of blocking!




**This gives you a different starting point to think of using the SCs in circuits more creatively!**

# Supercapacitor as a lossless voltage dropper – for high efficiency linear DC-DC converters

- A linear DC-DC converter is based on an energy dissipating series transistor




However, they are very inefficient

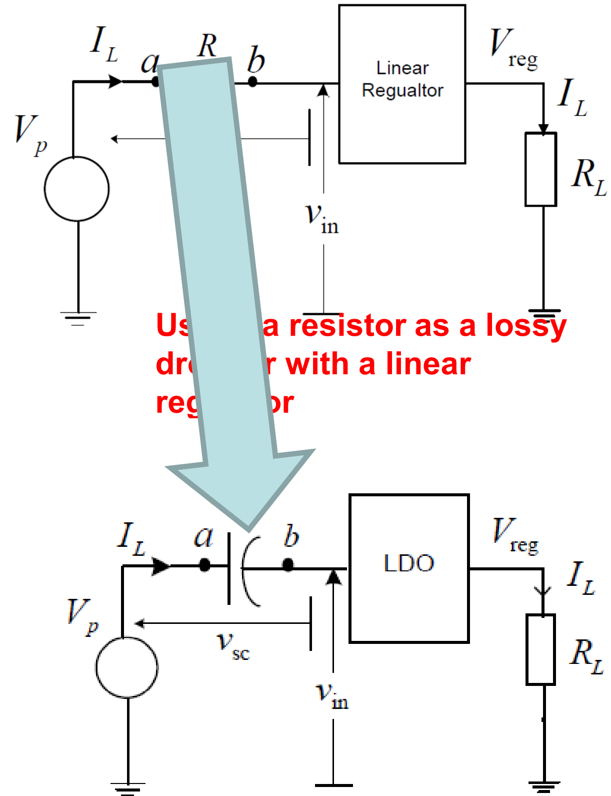
- 12-5V converter has a theoretical maximum efficiency of 42%
- 5-3.3 V converter gives you only 66% efficiency
- Efficiency is given by $\frac{V_o}{V_{in}}$

- If you insert a resistor in the series path energy dissipated in transistor can be part-transferred to the resistor
- However the overall efficiency will not improve!

**If a large capacitor is used instead of the resistor, it will store energy while dropping the voltage difference across transistor**

# Supercapacitor Assisted Low Dropout Regulator (SCALDO) technique

- A capacitor carrying a charge or discharge current of $I_L$ for a time period of $\Delta t$ changes the voltage across the capacitor by $\dfrac{I_L \Delta t}{C}$
- If the capacitor is very large this $\Delta V$ will be very small
- A supercapacitor (one million times larger than an electrolytic), will not be fully charged for a long time to block the circuit
- In supercaps, ESR is very small and this causes only a negligible voltage drop across ESR
- In larger SCs ESR can be significantly lower than the on resistance of commonly used MOSFETs




Us… a resistor as a lossy dr… r with a linear reg… or

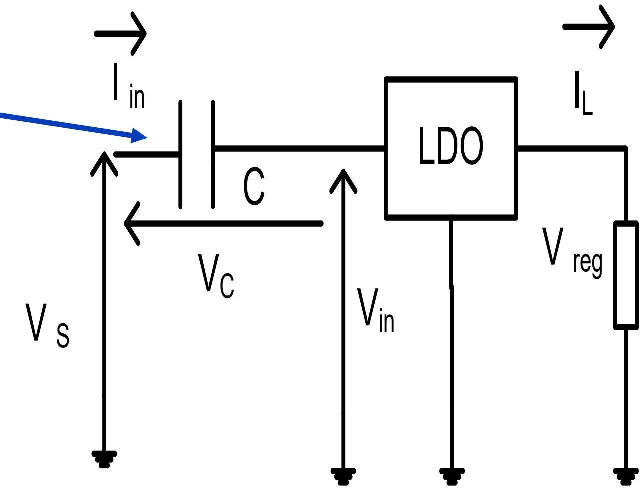
Use of a supercap as a lossless dropper with an LDO

**This allows us to use SCs as lossless droppers in linear power converters**

# Implementation of the SCALDO technique

A low dropout regulator (LDO) is a linear regulator, where input to output voltage difference is low, to keep the efficiency high.

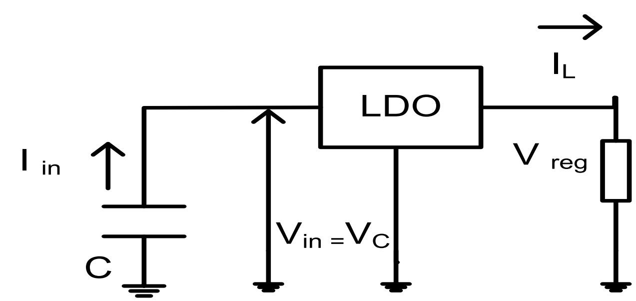
Now let us insert a SC pre-charged to Vc in the series path …




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 linear DC output converter with a 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

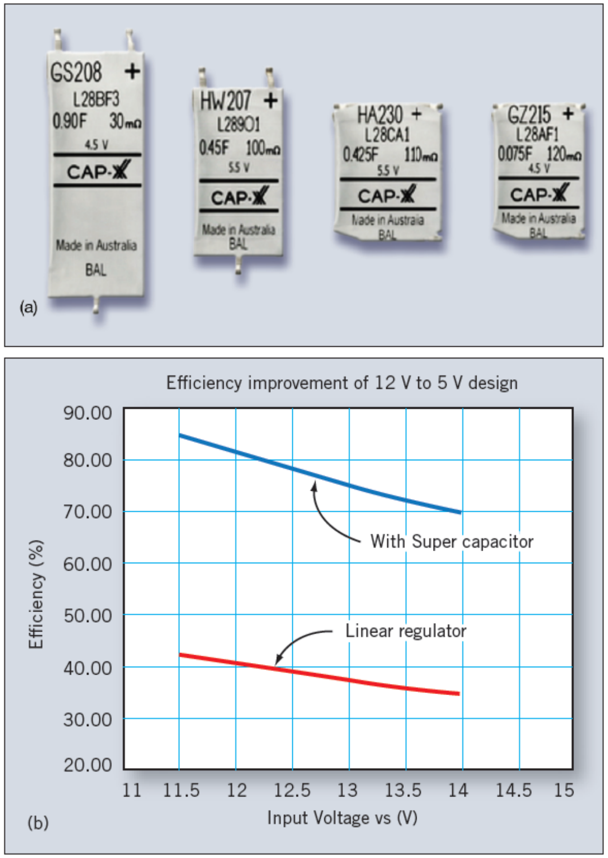



Fig. 3(a) Capacitor size reductions in an early prototype for 12-5V regulator super-caps used. (b) Shows efficiency improvements in 12-5 V regulator supercaps.

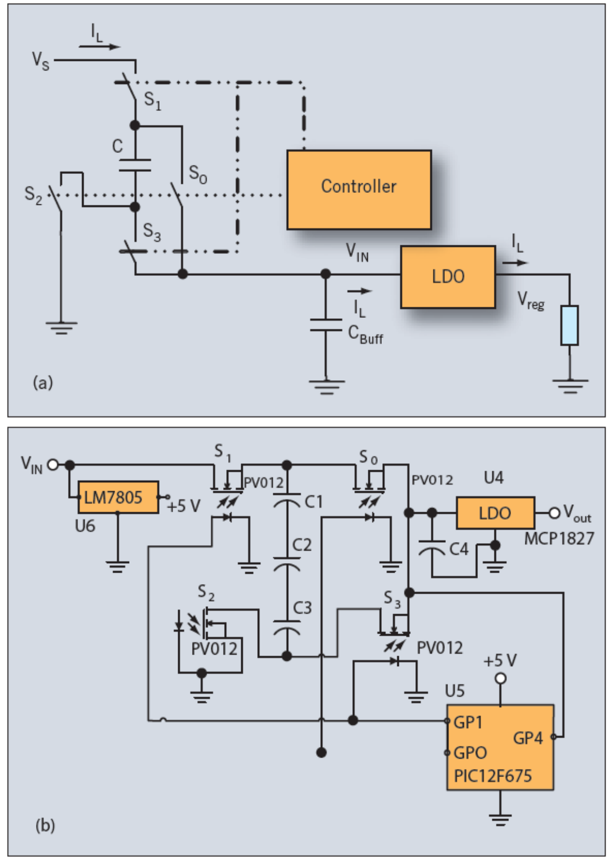
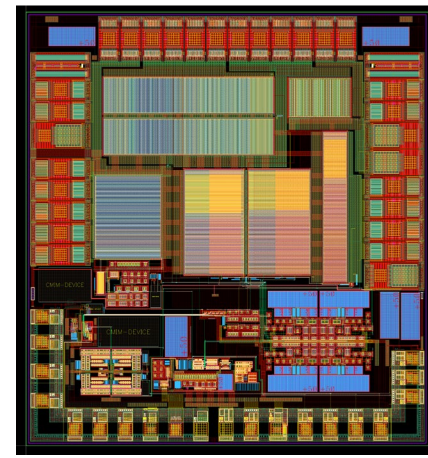



Fig. 4(a) The 12 V to 5V circuit to achieve efficiency improvements shown in Fig. 4(b). The implementation in Fig. 4(b) is shown using a PIC microcontroller.



**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

# SCALDO variations

## RS-SCALDO technique for high current converters

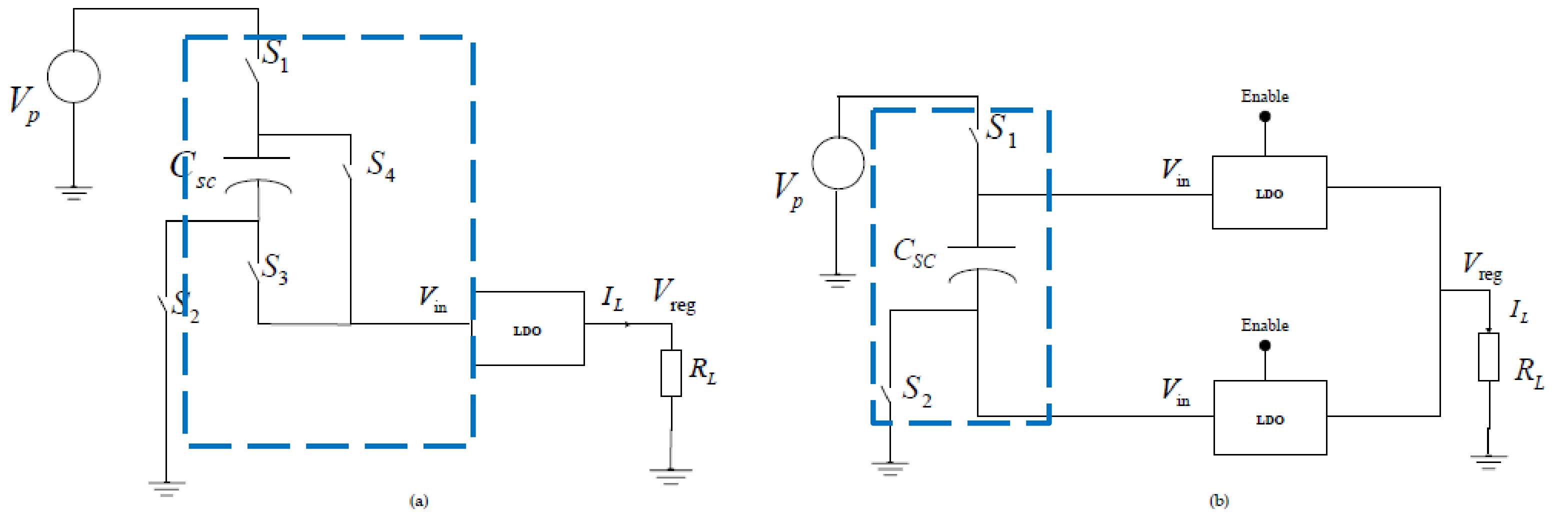


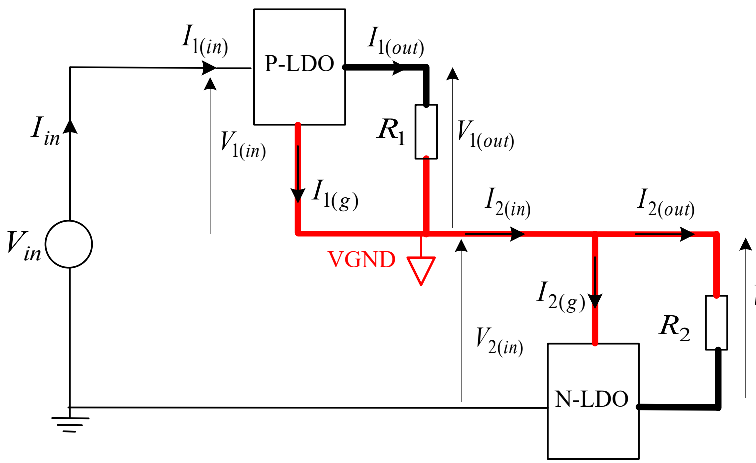

**Figure 1.1:** (a) Basic SCALDO configuration with single LDO and 4 switches (b) Modified RS-SCALDO (Reduced switches) configuration with two identical LDOs and two switches

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

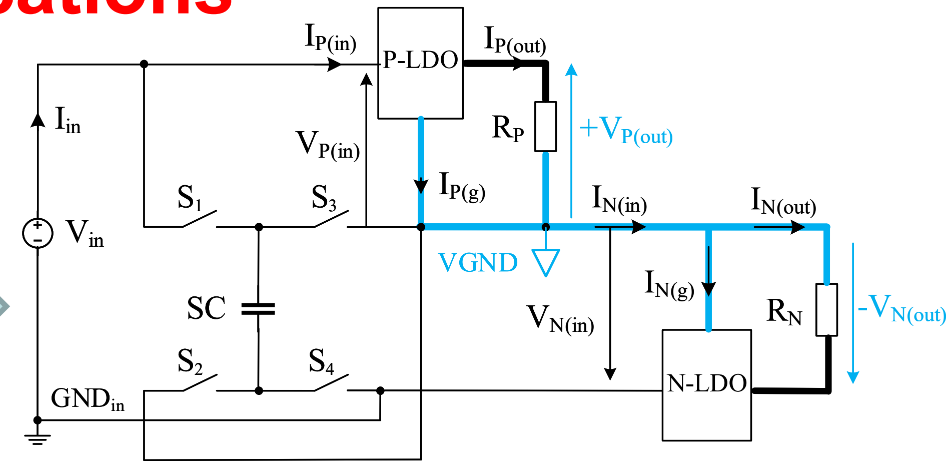
**Basis for linear VRM systems!**


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

# DO SCALDO Concept for Split-Rail Applications




Cascaded P-LDO and N-LDO




Dual-Polarity SCALDO Technique

- End-to-end efficiency: 81 %
- Switching frequency: 0.36 Hz
- Differential output power: 7.5 W
- Out put voltages : ± 5V
- Input voltage: 12 V DC


• Ref -Subasinghage, K., Gunawardane, K. & Kularatna, N. & Lie, T.K, Extending the Supercapacitor-Assisted Low-Dropout Regulator (SCALDO) Technique to a Split-Rail DC–DC Converter Application, IEEE Access, Vol 7, 2019.

# A summary on SCALDO

- 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 ---[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. ]

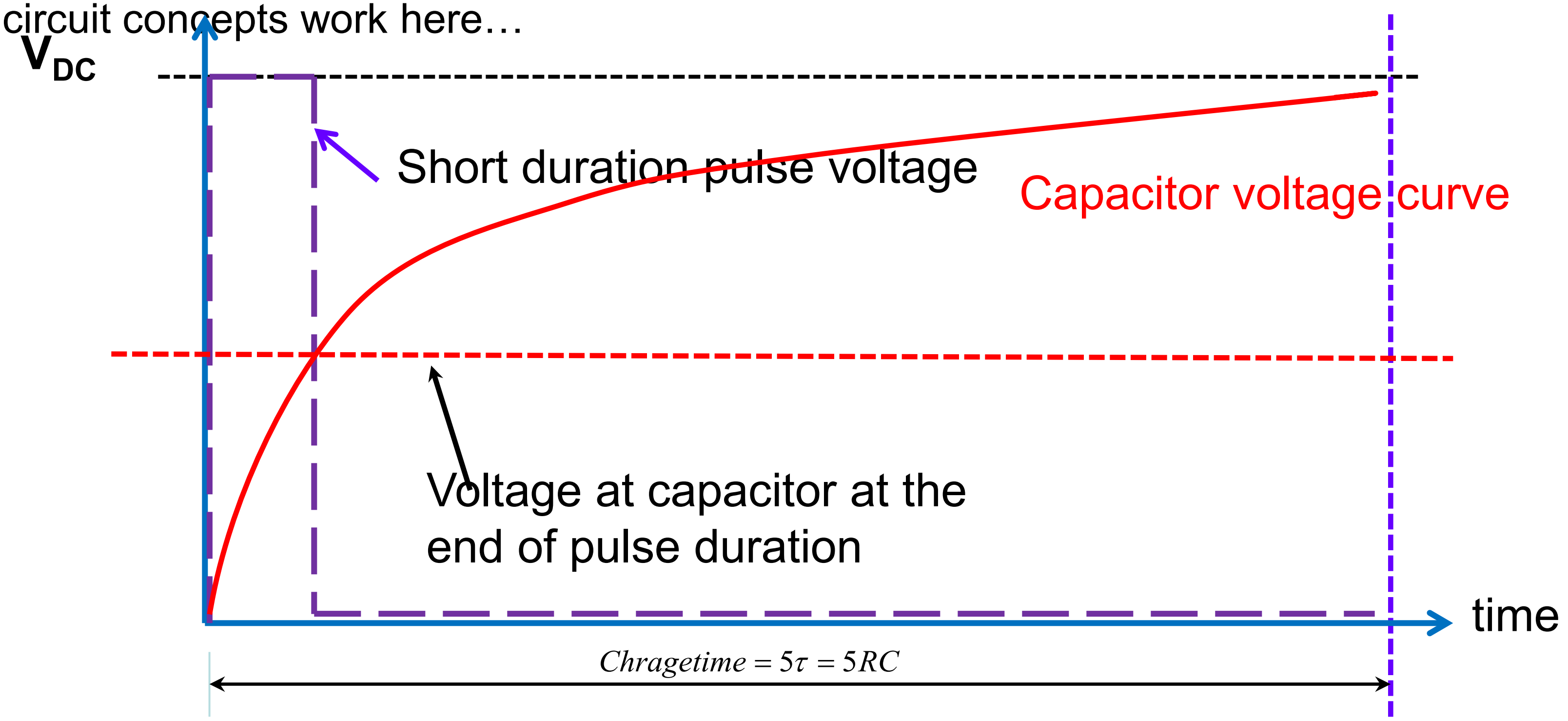
# Surge protectors based on supercapacitors: SC Assisted Surge Absorber (SCASA) Technique

# Can SCs absorb high voltage transients like lightning surges induced on power supplies?

- We have tested several types of SCs for their surge absorb capability using a Lightning Surge Simulator

- Most SCs can absorb transient HV surges of several 100 micro second durations

- Simple circuit concepts work here…



# 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*

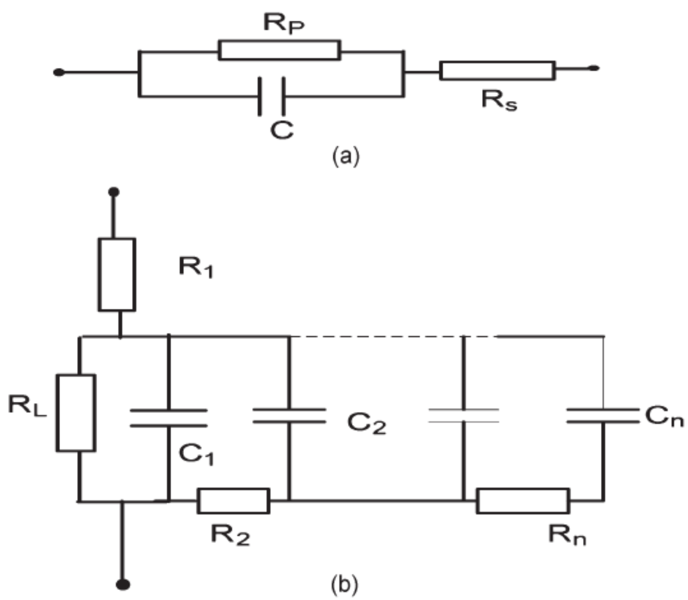



Fig. 2. SC equivalent circuits. (a) Classical equivalent circuit. (b) Ladder circuit.

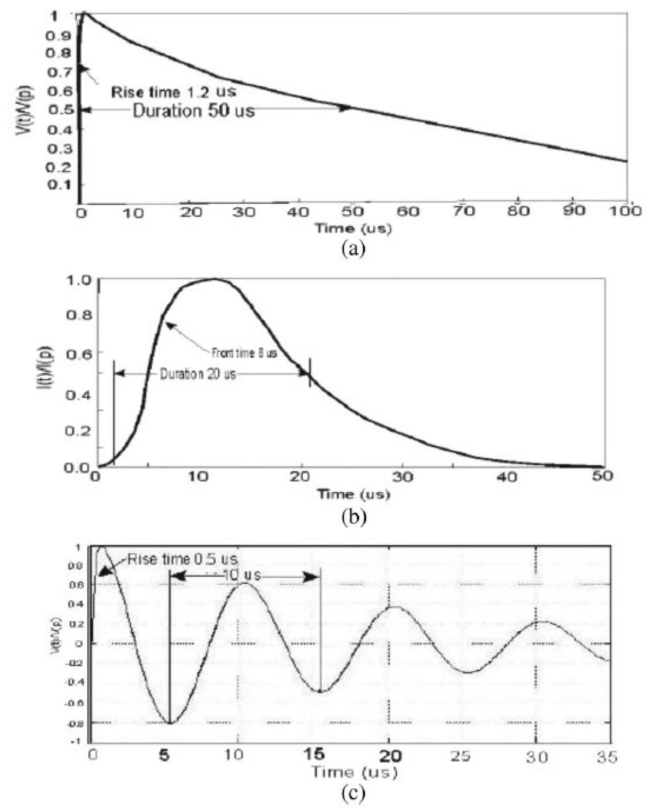
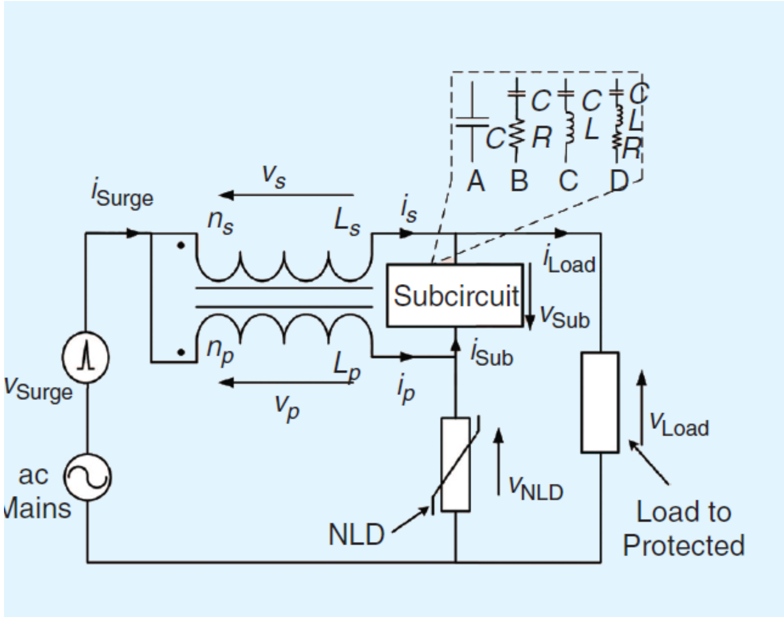



Fig. 3. Few examples of wave shapes defined in surge test standards. (a) Open-circuit voltage waveform. (b) Short-circuit current waveform. (c) Ring wave.

**Supercapacitors have very long time constants**

# (SCASA)- concept development

- A simple low cost symmetrical SC in the range of 1 to 100 F has energy absorption capability of 3 to 400 Joules
- A typical lightning surge carries anything between few Joules to few 100 Joules.
- However, they are very low DC voltage rated devices, and can not be placed across a power line (Live to Neutral) directly like a MOV or a BBD
- Also it makes very low impedance across the terminal at 50 or 60 Hz, determined by 1/ ωC
- Given the above, a special configuration of a surge protection circuit was developed [**US patent** 9,466,977 B2, **Power and telecommunications surge protection apparatus**, Oct 2016]

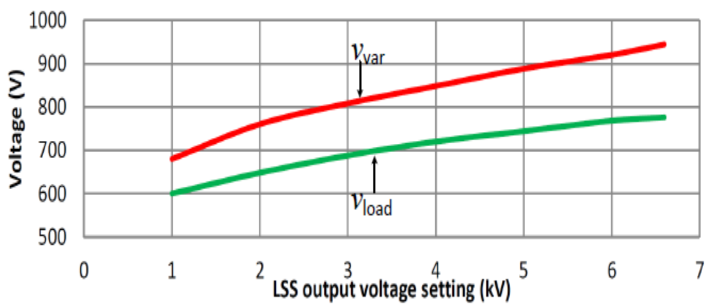



**The SCASA circuit topology is based on a SC sub-circuit, combined with a coupled inductor and a typical MOV**

# 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

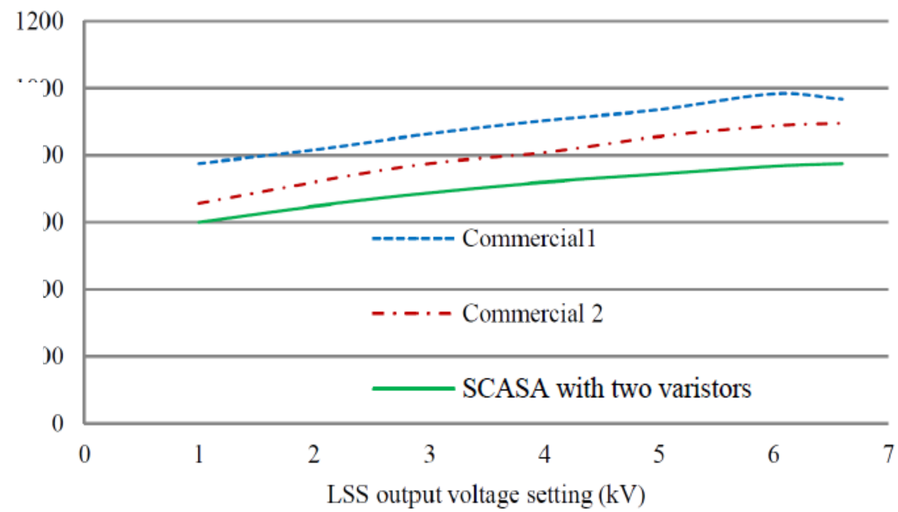




**Figure 5.19:** Performance comparison of SCASA with two commercial surge protectors

**In SCASA, 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

# 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
- 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

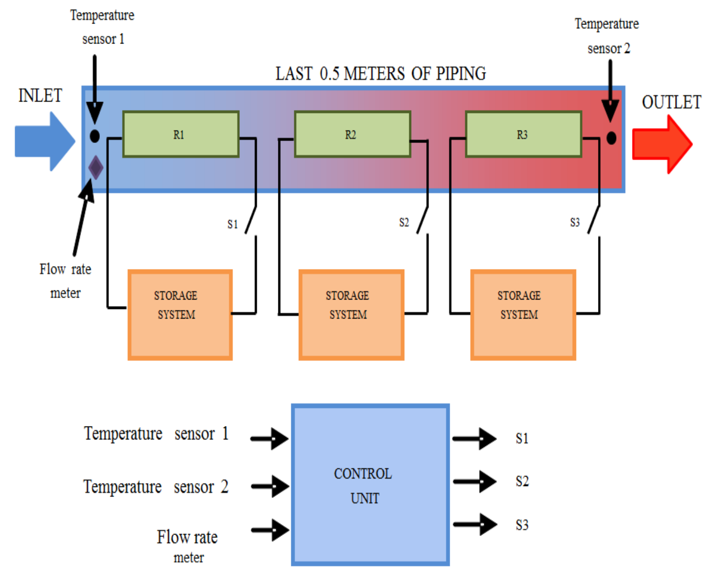
## Why it is not easy to solve the problem

- Maximum power we can draw from a wall socket is 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]

## Energy and power requirements for rapid water heating

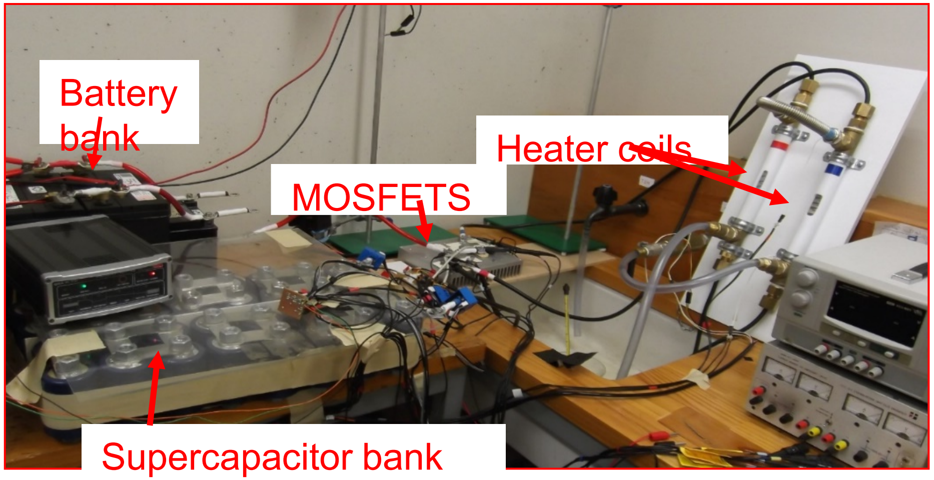
| Flow Rate ($L\,min^{-1}$) | 4 | | | 6 | | |
|---|---|---|---|---|---|---|
| Temperature Rise (°C) | 20 | 30 | 50 | 20 | 30 | 50 |
| Total Energy (W h) | 46 | 70 | 116 | 70 | 105 | 175 |
| Average Power (kW) | 5.6 | 8.4 | 14 | 8.4 | 12.6 | 21 |
| Average Current at 50 V (A) | 112 | 168 | 280 | 168 |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

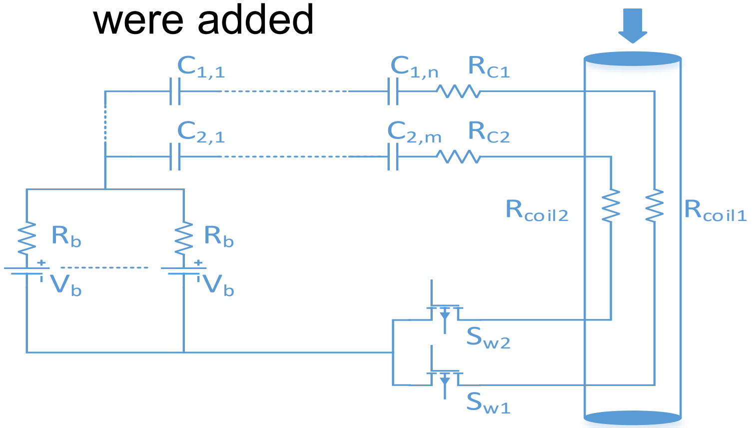
## SCATMA

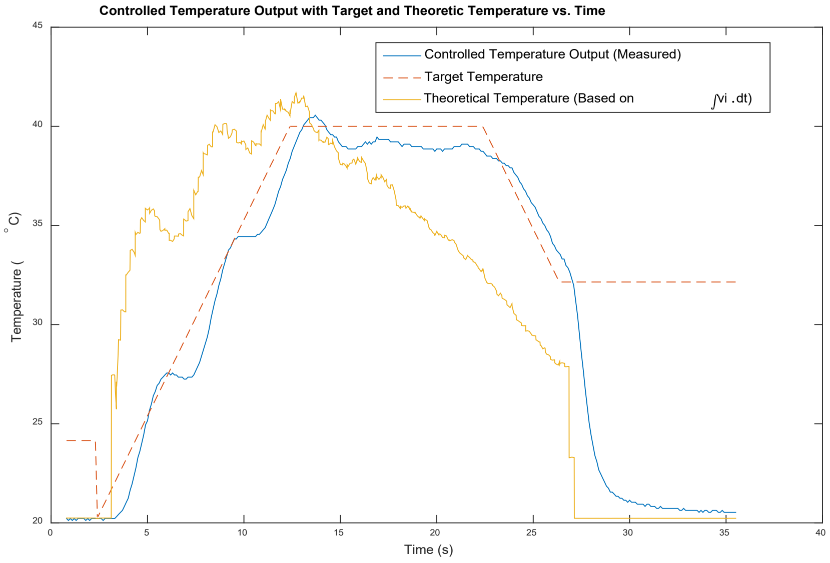


# Implementation

- A SC bank of 50 to 150 Wh with very low ESR was developed
- It operates from a DC source less than 50 V to be safe next to a water faucet
- 10 -20 kW capable heater coil was built and placed inside the last section of plumbing before faucet
- A water fallow rate sensor and a microprocessor based control units with high current MOSFET switches were added




**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.

# 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**

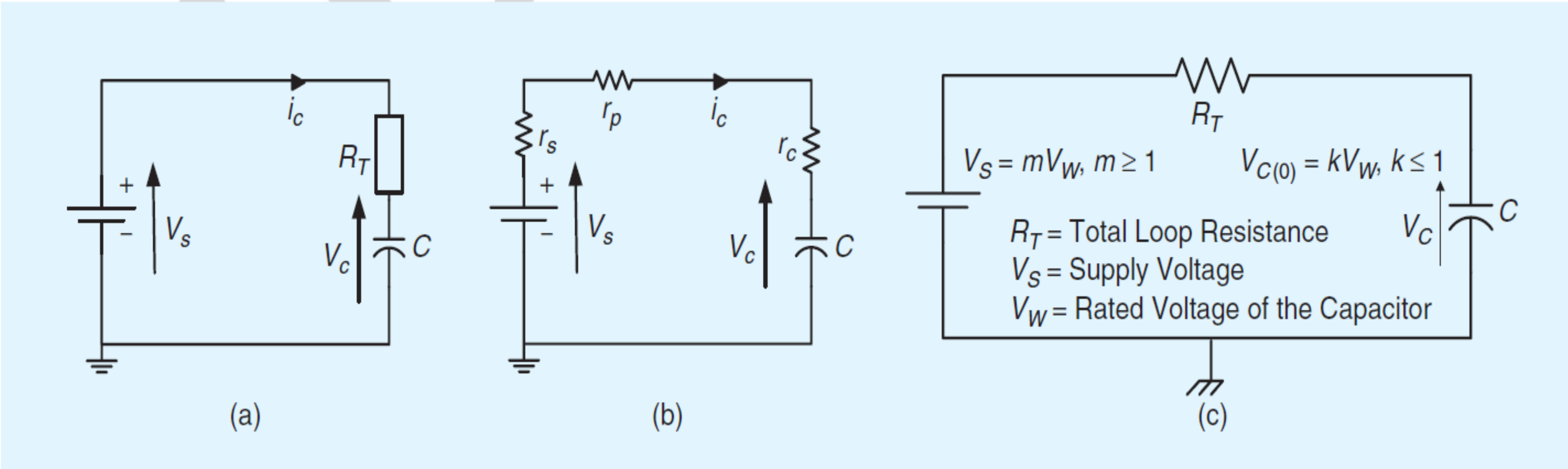



Figure 3 – The generalized case of the R–C circuit. The (a) simple textbook case with a capacitor starting from zero voltage, (b) resistive components contributing to loop resistance ($R_T$), and (c) the SC in a precharged condition.

- 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**

# SCALoM Theory

- All what we achieve is the reduction of losses in parasitic components of the RC circuit
- And, extending the circuit time constant by several orders due to supercapacitor for low speed operation for less dynamic losses

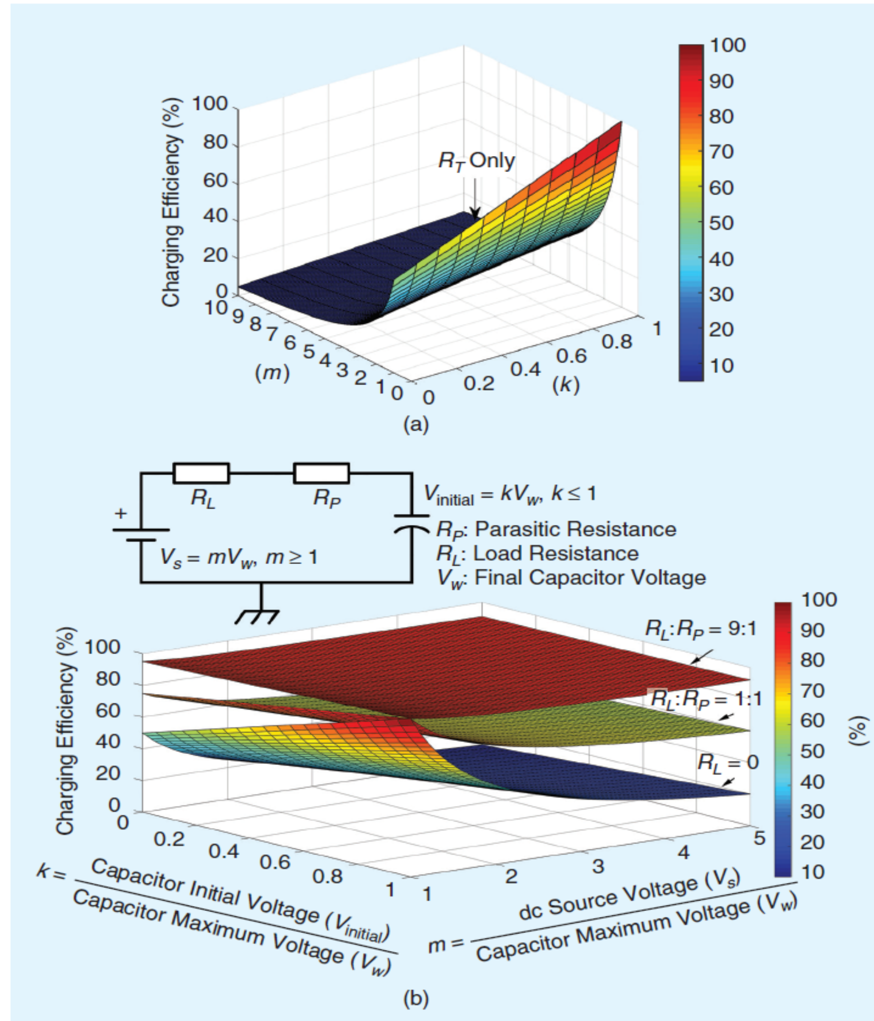
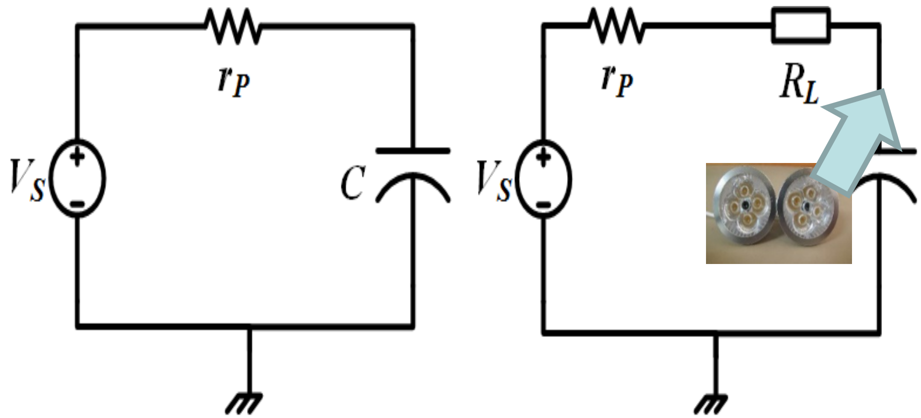



Figure 4 – The SCALOM concept. The (a) efficiency versus factors *m* and *k* for the circuit in Figure 3, and (b) overall efficiency improvement versus *m* and *k* with the insertion of useful resistor $R_L$ into the loop [14].

**Ref : Kularatna, N. & Jayananda, D., Supercapacitor Based Long Time Constant Circuits: A Unique Design Opportunity for New Power Electronic Circuit Topologies, IEEE Industrial Electronics Magazine, June 2020 issue (In print process ).**

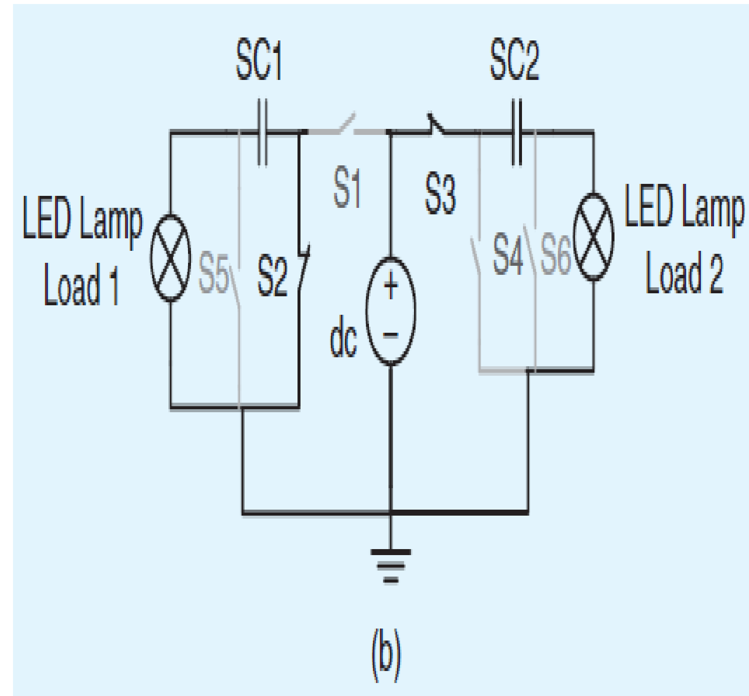
# SC assisted LED lighting for DC microgrid and renewable energy systems

## SCALED Technique



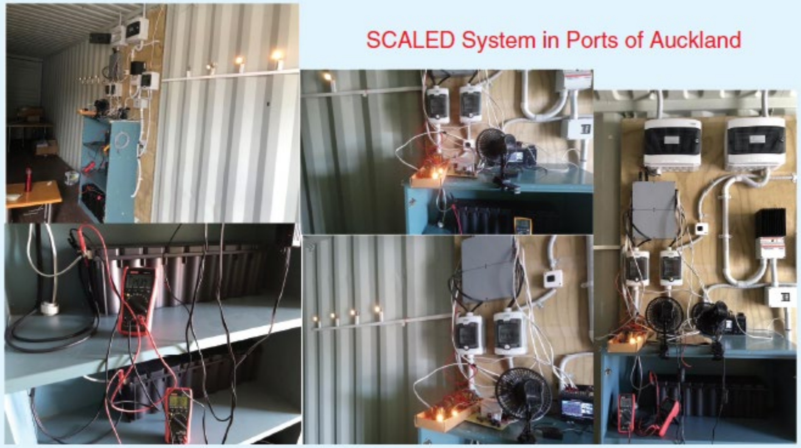

(a) (b)

- 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**

# SCALED System was tested in NZ at Auckland Port



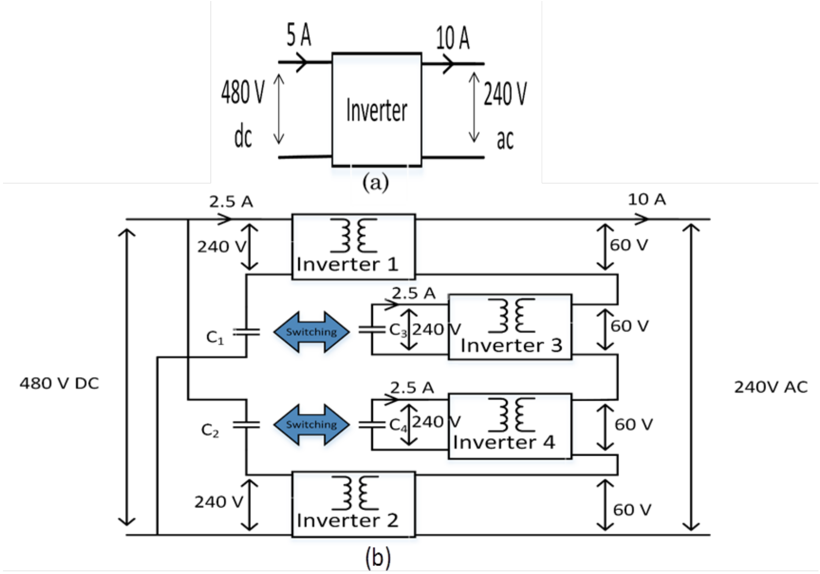

(g)

- SCALED concept can be extended to DC whitegoods and air conditioners etc.
- This research is in progress now
- Details of the SCALED is published in IEEE/ IET

Ref: (2020) D. Jayananda, N. Kularatna & Steyn-Ross, D. A. Supercapacitor Assisted LED (SCALED) technique for renewable energy systems: A low-frequency design approach with short-term DC-UPS capability eliminating battery *IET Renewable Power Generation, Vol 14,* doi: 10.1049/iet-rpg.2019.1307 (2020), Early Access.

# 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 make us of commercial EDLCs in many more applications and much more versatile than in simple energy storage systems….**

# Thank you…

**5th May 2020**