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

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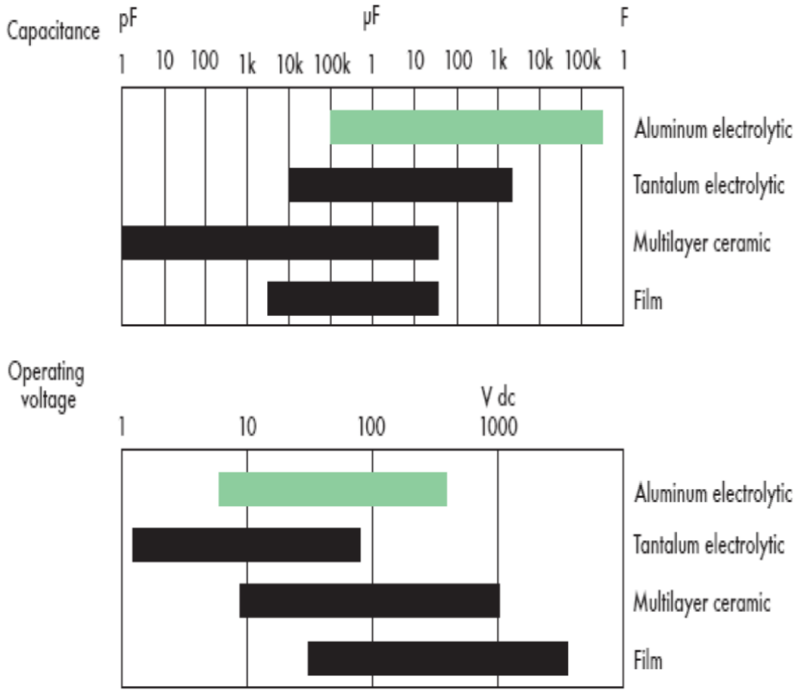
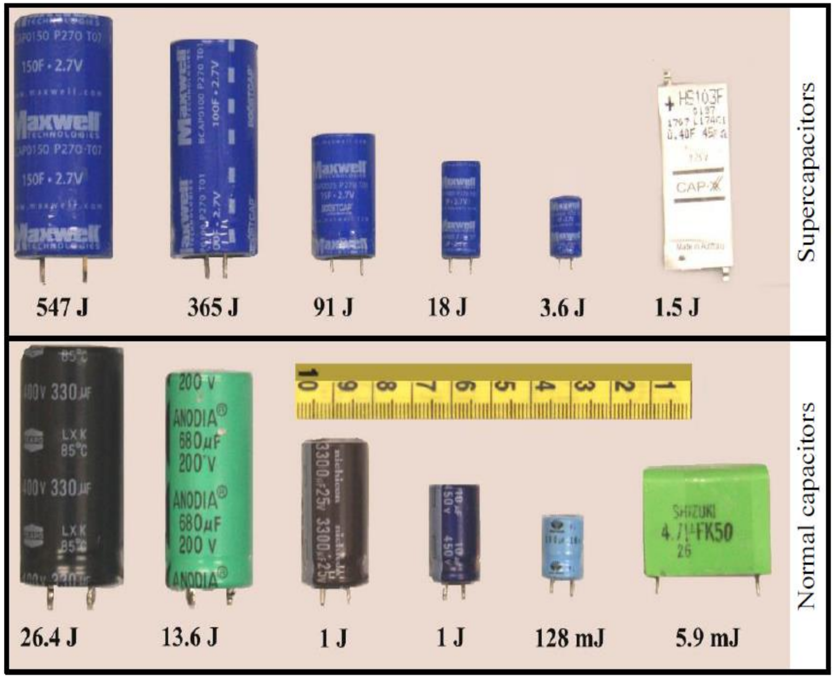
# Normal capacitors and their limits




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**

# Supercapacitors versus batteries

## Ragone Plot

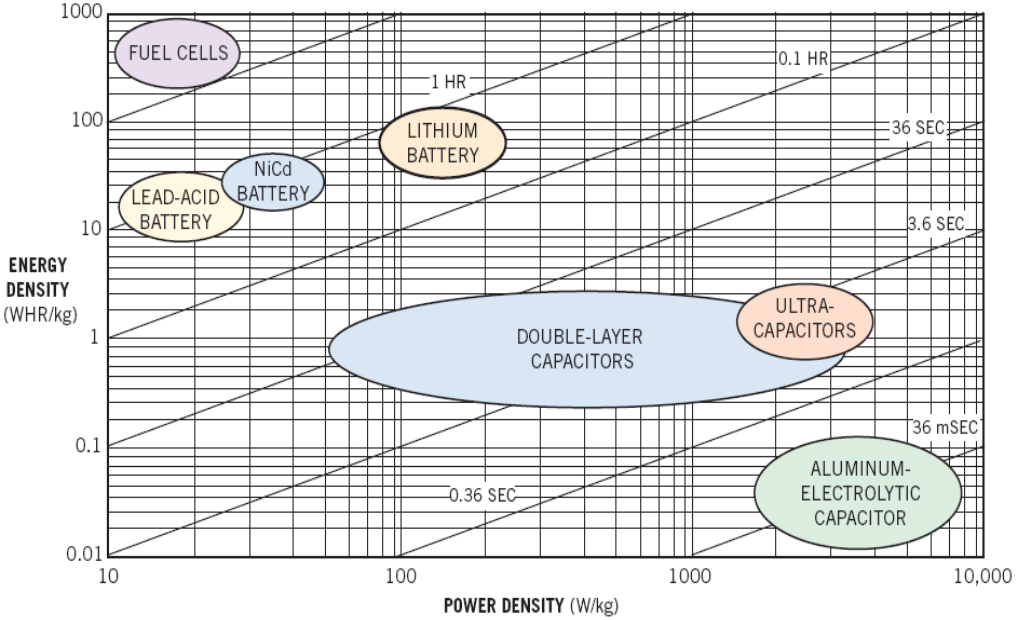
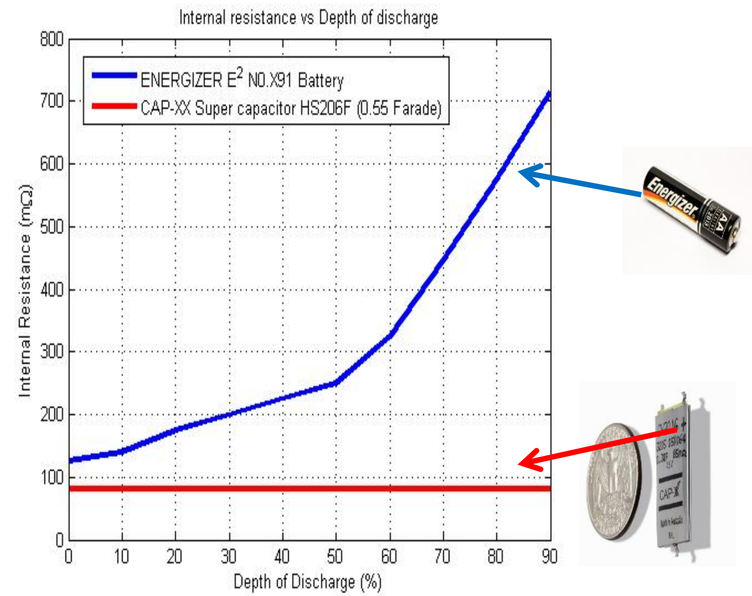



**Figure 1** Graphing energy density against power density, conventional batteries occupy the top-left position, and conventional aluminum-electrolytic capacitors occupy the bottom-right. Supercapacitors bridge the space between. Diagonal lines are lines of equal discharge time into a specified load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

54 EDN | January 9, 2003

## Internal resistance with depth of discharge




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

# SCs versus electrolytics

| 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.**

# 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

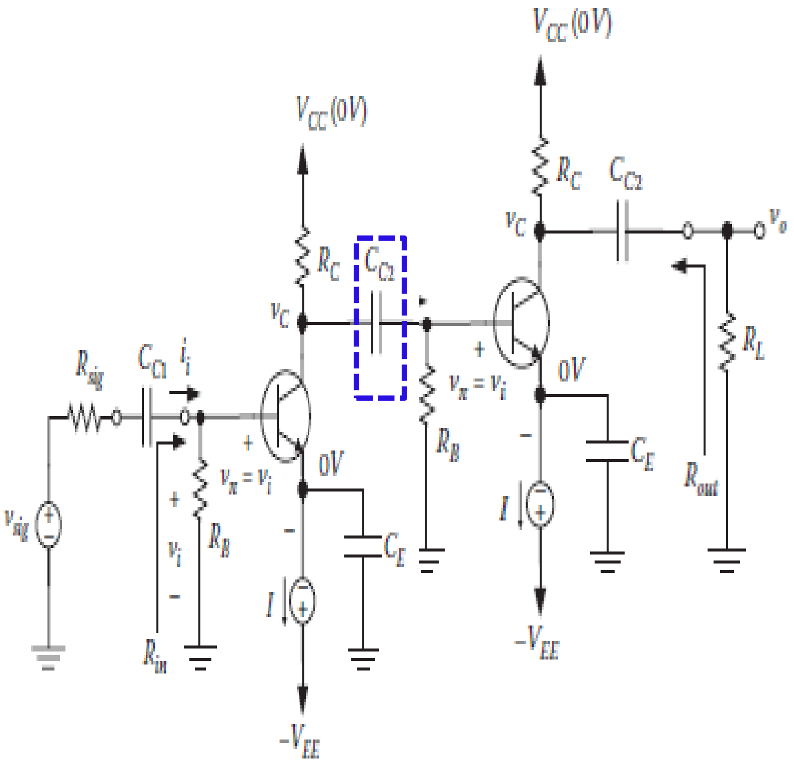
**Common supercapacitor applications are in**

- 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

# Capacitors used in simple DC blocking circuits

- We use electrolytics and ceramics as simple DC blocking elements in amplifiers
- When a circuit is powered, the DC blocking capacitor charges to the difference in voltages within micro to millisecond time periods
- Typical values used are from few nano-farads to tens of microfarads
- If we replace a 1 µF blocking capacitor with a 1 F capacitor the circuit will 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!**

# Typical characteristics of SCs useful in 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

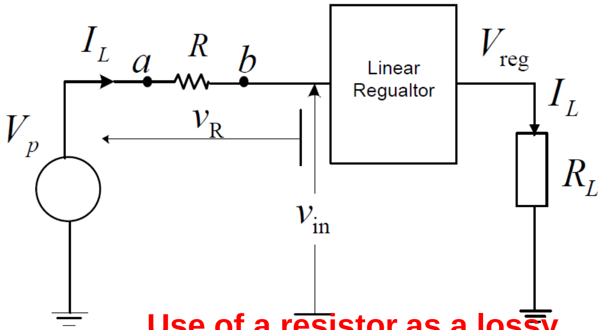

Source: Cap-XX , Australia



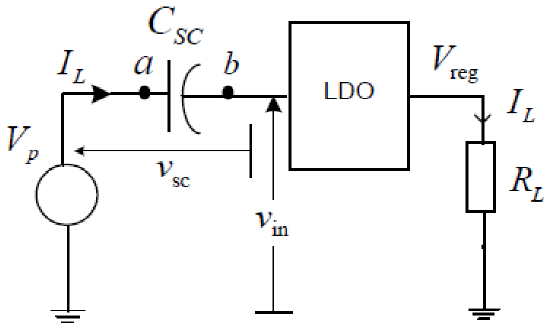

**Smaller ESR of SCs allow them to be used for short term high power delivery**

# Supercapacitors as lossless voltage droppers in linear power converters

- 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




**Use of a resistor as a lossy dropper with a linear regulator**

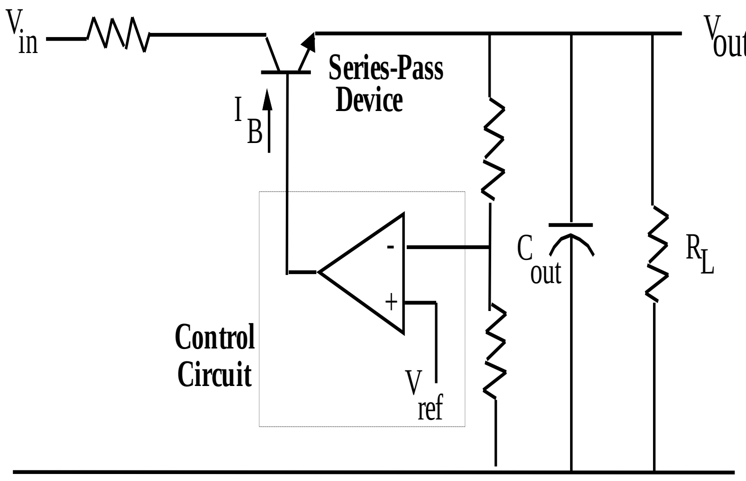



**Use of a supercap as a lossless dropper with an LDO**

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

# How SCs help increasing the efficiency of linear DC-DC converters

- Linear DC-DC converters have low noise RFI/EMI free DC output
- 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 $\frac{V_o}{V_{in}}$



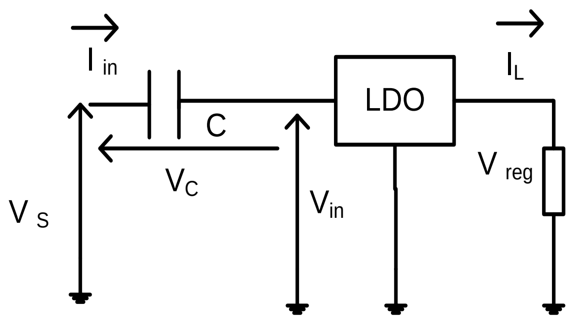

In a typical linear regulator series pass transistor wastes energy

- Higher the voltage difference between the input and output side the loss is higher
- In low dropout regulators (LDO) efficiency is high due to smaller input-output voltage difference
- If we can insert a lossless voltage dropper in the series path we can reduce the waste of energy
- A capacitor in series can help here, as far as it does not block the circuit

**SC assisted low dropout regulator (SCALDO) technique makes use of a supercapacitor to achieve a lower input-output voltage difference**

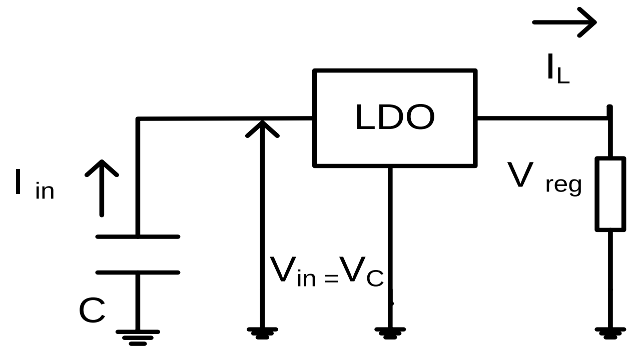
# Basic concept of the SCALDO technique

**Use a very large capacitor in series with LDO**




- Series SC charges until it reaches the minimum input voltage of LDO $V_{in,(min)}$
- At the end of the charging time voltage across the SC reaches $(V_s-V_{in,(min)})$
- This supercapacitor will be discharged later up to $V_{in,(min)}$, $V_s > 2V_{in,(min)}$

**Reuse of energy stored in the first part of the cycle**




- Series SC charges until reaches min. input voltage of LDO $V_{in,(min)}$
- At the end of the charging time voltage across the SC reaches $(V_s-V_{in,(min)})$
- To discharge this supercapacitor later up to $V_{in,(min)}$, $V_s > 2V_{in,(min)}$

**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

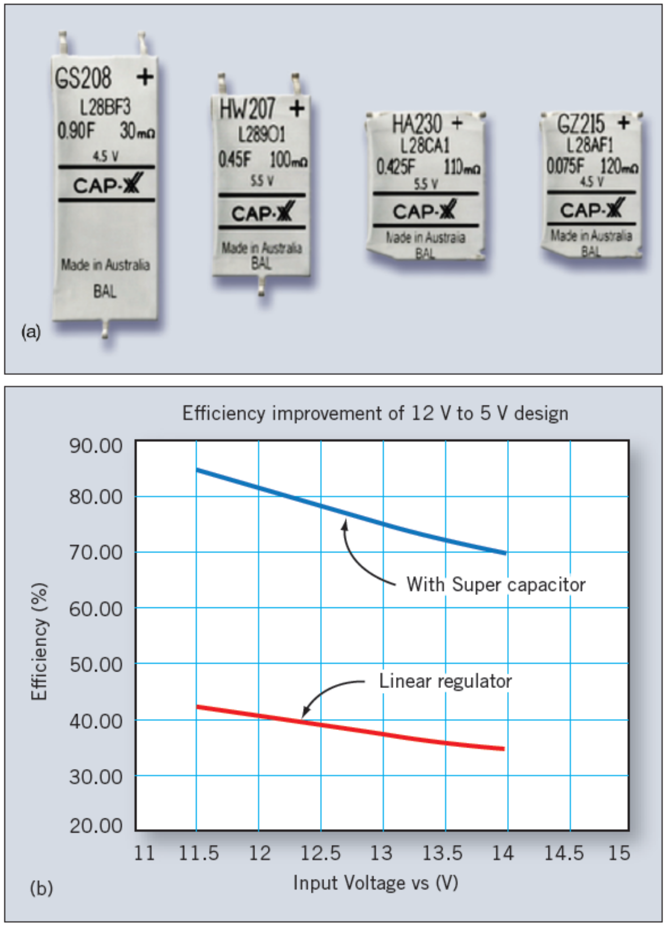



Fig. 3(a) Capacitor size reductions in an early prototype for 12-5V regulator super-caps used. (b) Shows efficiency improvements in 12-5 V regulator supercaps.

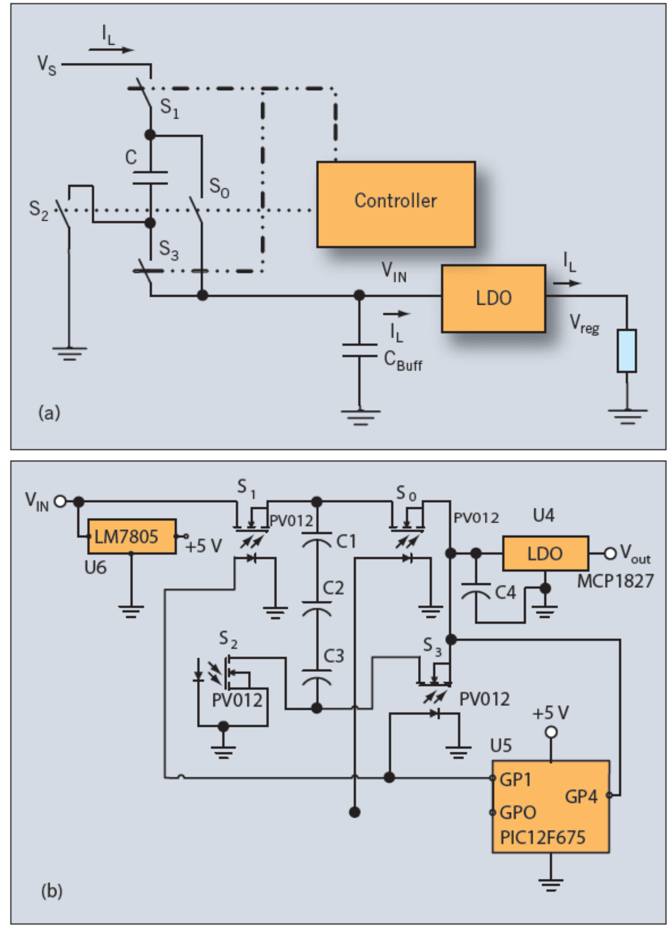



Fig. 4(a) The 12 V to 5V circuit to achieve efficiency improvements shown in Fig. 4(b). The implementation in Fig. 4(b) is shown using a PIC microcontroller.

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

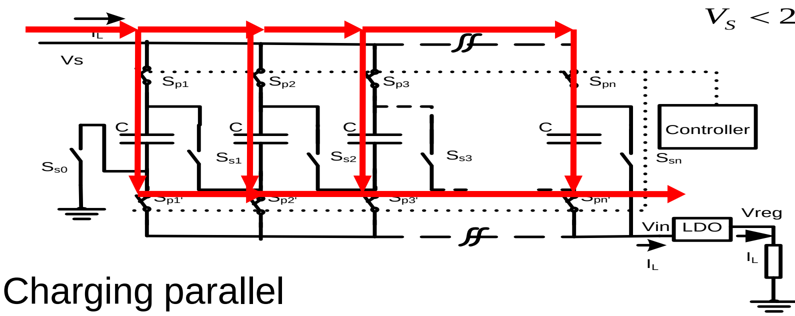
# SCALDO Applications and Adavantages

- SCALDO uses the low ESR advantage and the large capacitance of the device
- Topology runs at very low frequency (milli-hertz to few 10s of Hz)- No RFI/EMI issues
- Load always see the high quality output of a linear regulator
- **It helps with an efficiency multiplication factor in the range of 1.33 to 3**

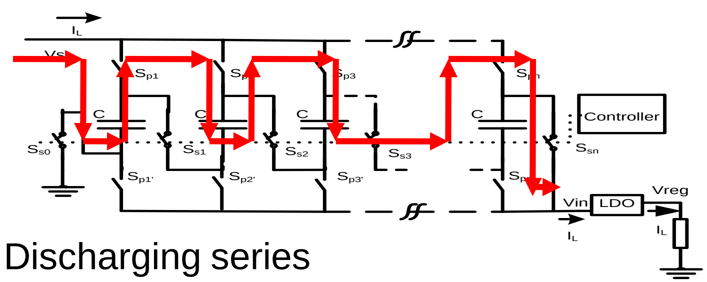
    For a 12-5V converter it is a factor of 2 (giving 84% theoretical efficiency)
    For a 5-3.3 converter this factor is 1.33 ( 88% theoretical efficiency)
    For a 5-1.5V converter this factor is 3 (90% theoretical efficiency)

# SCALDO Configurations for 5-3.3V and 5-1.5V requirements

$V_S < 2V_{in,(\min)}$

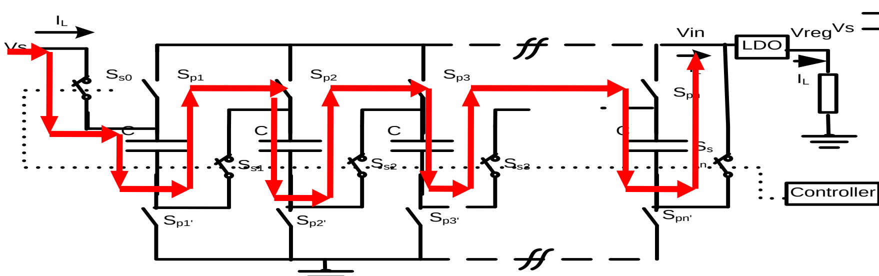



Charging parallel

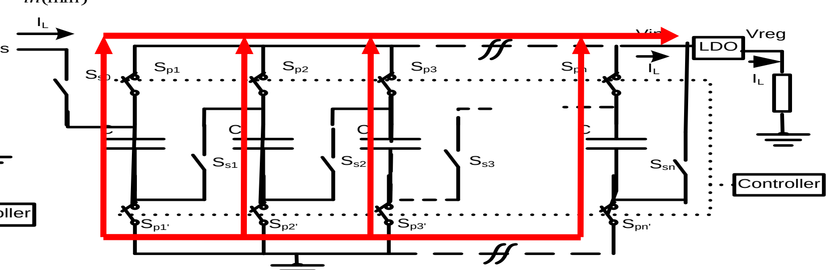



Discharging series

$V \ > 3V_{in(\min)}$




Charging series




Discharging parallel

# SCALDO variations

## RS-SCALDO technique for high current converters

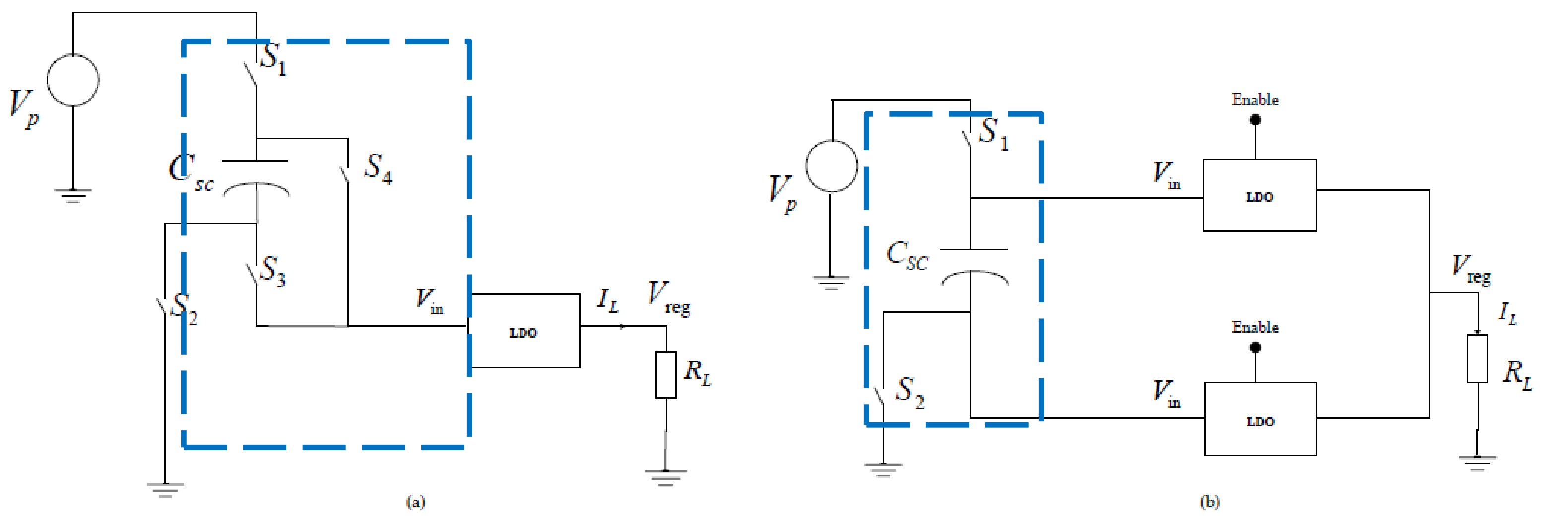



**Figure 1.1:** (a) Basic SCALDO configuration with single LDO and 4 switches (b) Modified RS-SCALDO (Reduced switches) configuration with two identical LDOs and two switches

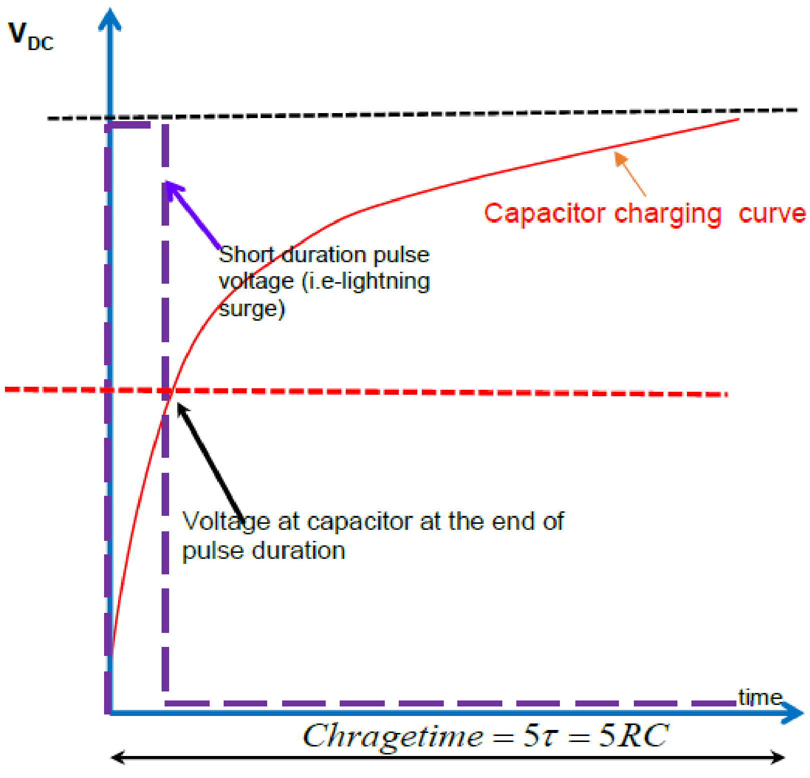
**By splitting the LDO into two half size LDOs we can reduce the number of powers switches**

**Basis for linear VRM systems!**

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

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

Large time constant circuit excited by a short duration step-voltage




- 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?**

# Due to their long time constant circuits SCs can absorb kilovolts order surges!

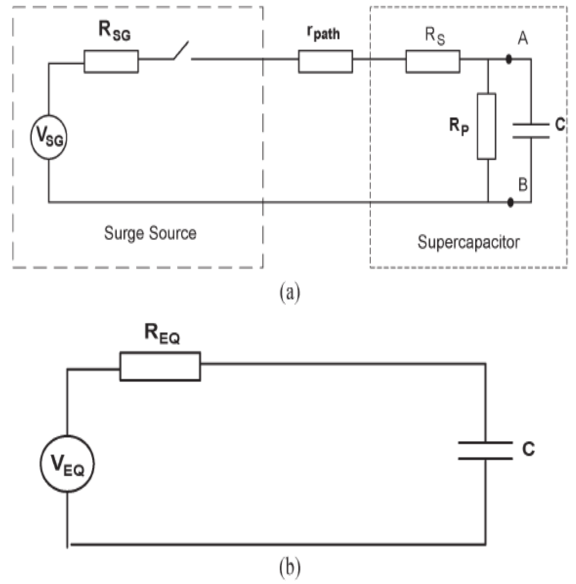



Fig. 5. Surge source connected to an SC. (a) Case with a simplified equivalent circuit of an SC. (b) Simplified Thevenin equivalent circuit.

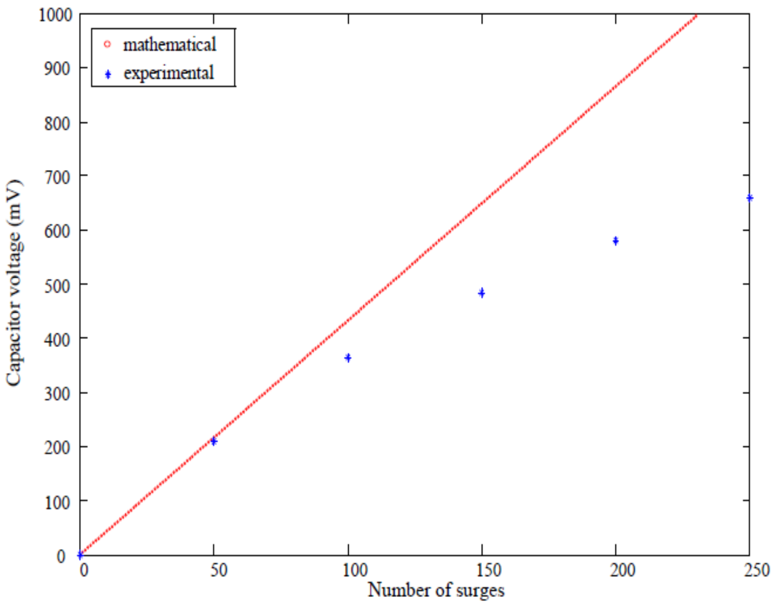



**Figure 4.6:** Applying consecutive surges to a 1 F supercapacitor; experimental vs simulated data

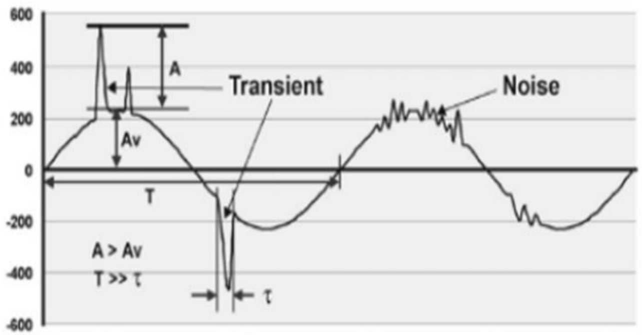
- **This indicates that due to very long time constants, SC can't be destroyed by short duration transient surge voltages**
- **We tested three different commercial families of SCs and reconfirmed this practically**

4942 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 58, NO. 10, OCTOBER 2011

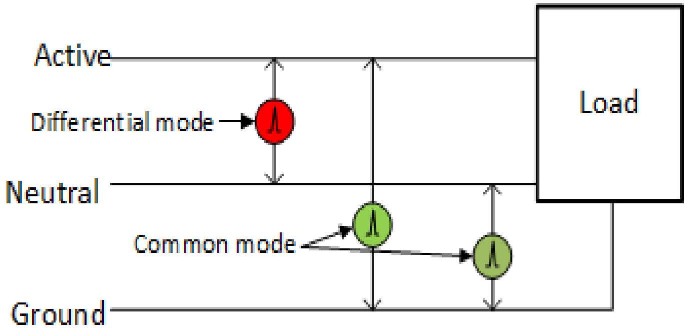
Surge Capability Testing of Supercapacitor Families Using a Lightning Surge Simulator

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

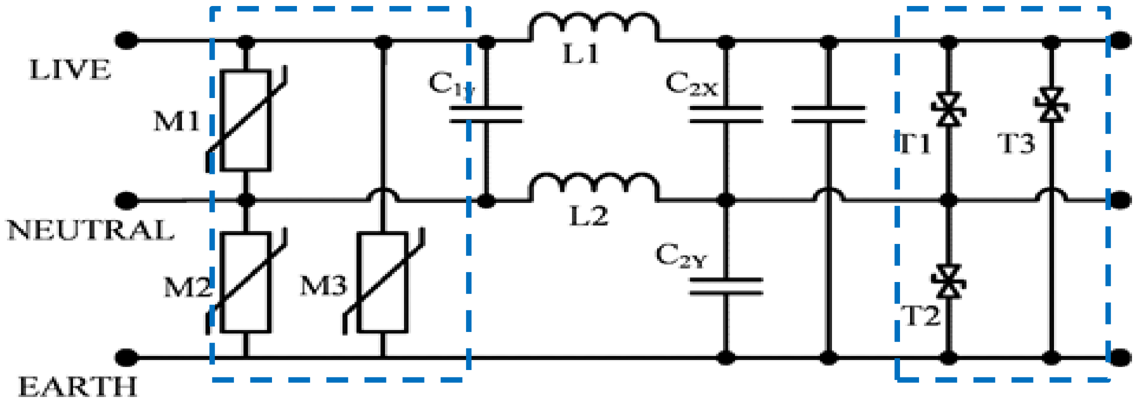
# Typical surge protector circuits and power line transients




Power line surges



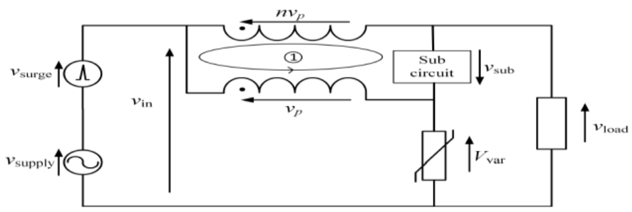

Differential and common mode surges




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

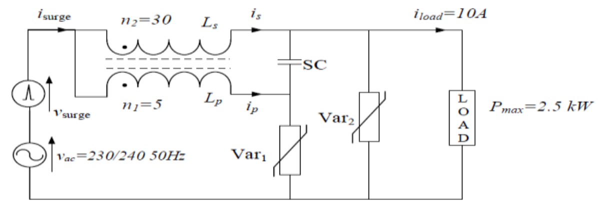



**Figure 5.16:** The SCASA technique with an additional second varistor for further protection

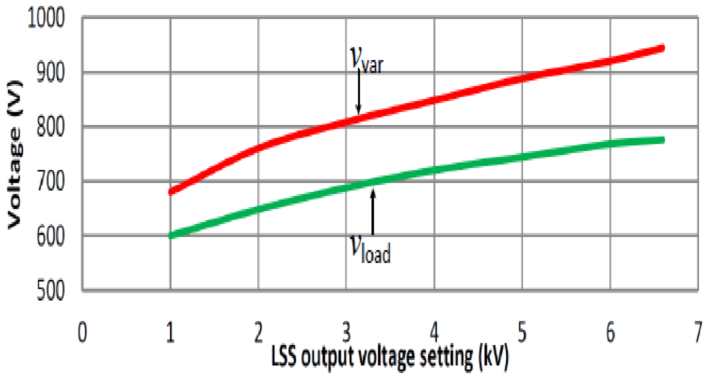
Practical implementation in a commercial design


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 |



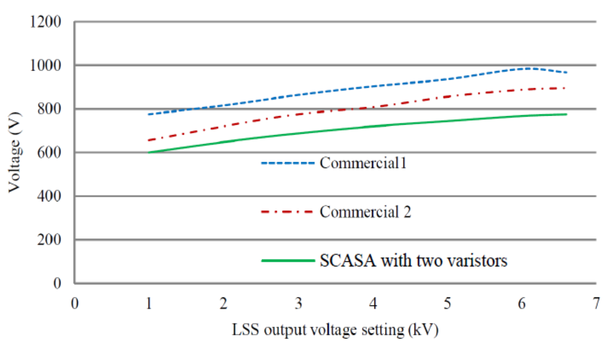




**Figure 5.19:** Performance comparison of SCASA with two commercial surge protectors

**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

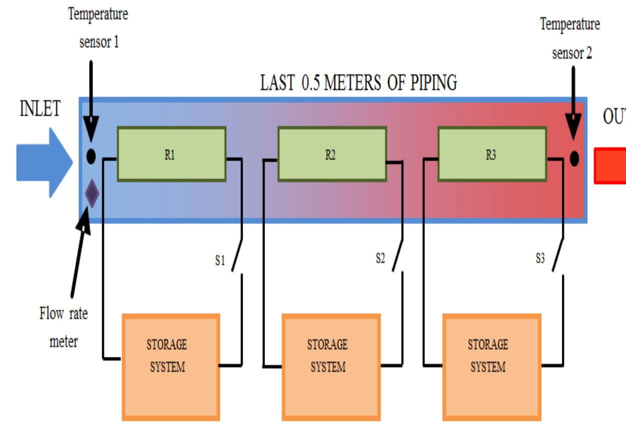
## Well-known problem at water faucets

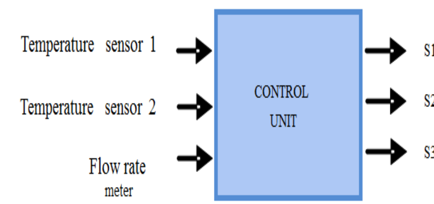
- In our home environments central water heater is at a distant location from individual faucets
- This makes cold water storage between the central heater and the faucet
- Result is delayed hot water at the faucet
- Delay can be anything from about 10 seconds to a minute depending on the length of the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

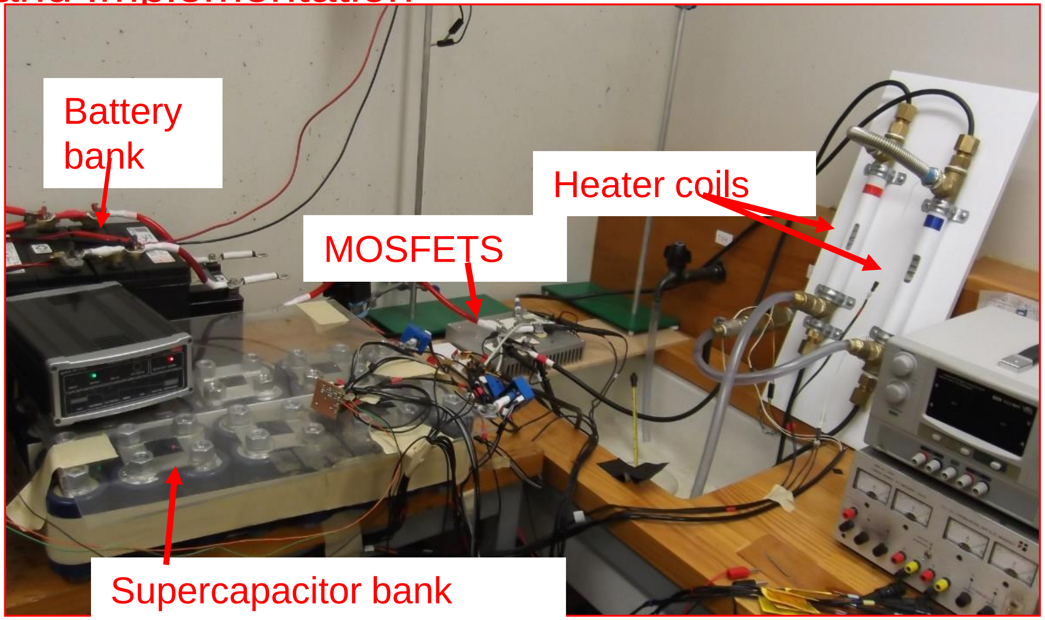


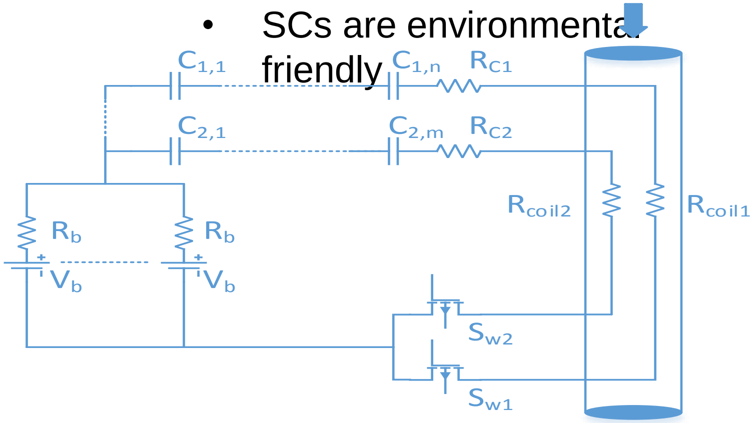



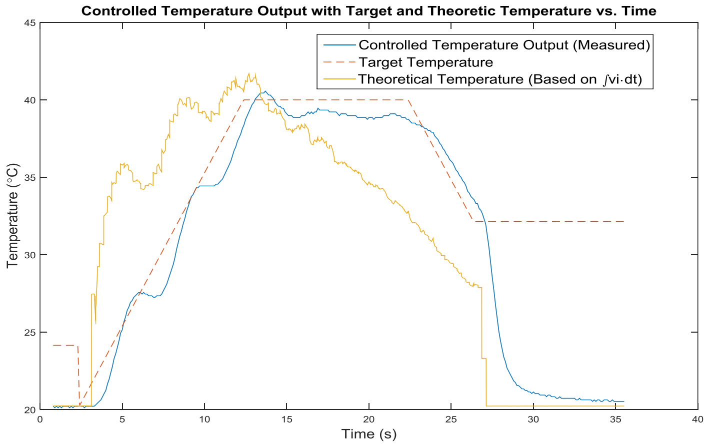

| Flow Rate ($L\,min^{-1}$) | 4 | | | 6 | | |
|---|---|---|---|---|---|---|
| Temperature Rise (°C) | 20 | 30 | 50 | 20 | 30 | 50 |
| Total Energy (W h) | 46 | 70 | 116 | 70 | 105 | 175 |
| Average Power (kW) | 5.6 | 8.4 | 14 | 8.4 | 12.6 | 21 |
| Average Current at 50 V (A) | 112 | 168 | 280 | 168 |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

# More SC assisted circuit topologies under development

## Early developments and achievements

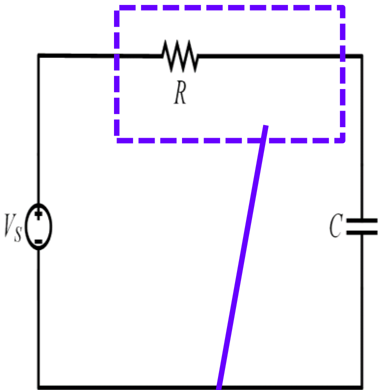
- Development of the SCALDO technique indicates the power of very large capacitors
- SCALDO is based on circumventing the capacitor charging losses and a large time constant circuit combined
- SCASA was making use of large time constant property of SCs and SCATMA was based on the very low ESR of large SCs

## The above work opened up the potential of additional SC assisted topologies

- SC assisted high density inverter- SCAHDI ( Inspired by Google's the Little Box Challenge)
- For DC Microgrid area with 12 V LED lighting SC assisted LED systems (SCALED)

**In both cases, capacitor charging loss in a resistive charging loop is circumvented by inserting a useful load such as a LED lamp load or a inverter**

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




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

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

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

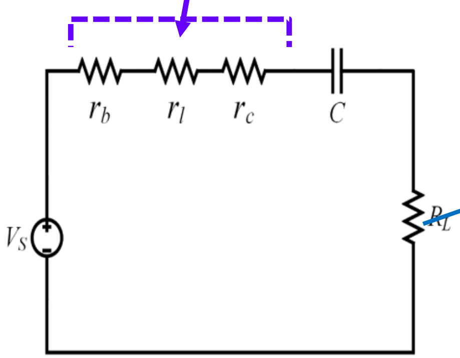
$$E_{r_l} = \left(\frac{r_l}{r_b+r_l+r_c+R_L}\right) . E_{Loss}$$

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

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

- The $R_L$ utilizes the wasted energy;

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

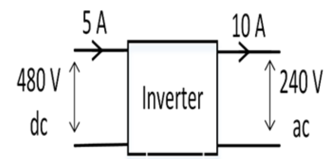



Inserting useful resistive load in the charging loop

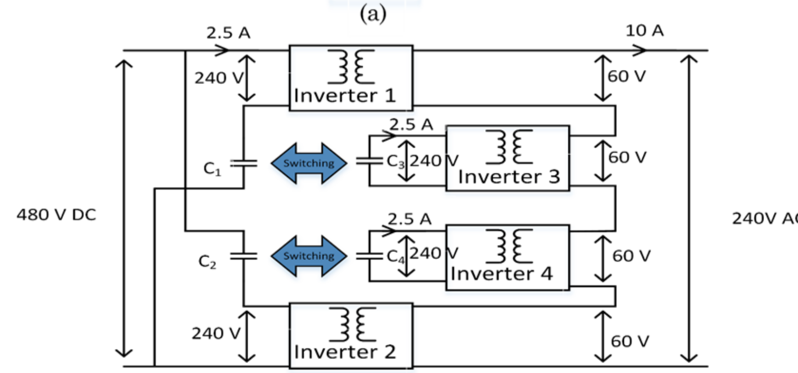
**This concept was used in the SCALDO technique, where $R_L$ was the loaded LDO**

## 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




(a)




(b)

**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…..

## Question Time…

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