

# **Supercapacitor assisted extra low frequency power converters and surge protectors: Applying Supercapacitor Assisted Loss Management Concept in practical applications**

## **ABSTRACT**

Traditionally, supercapacitors are used as energy storage devices, replacing or hybridizing with batteries. Typical applications include UPS, power quality enhancers, automotive, electric vehicles and portables. However, if a supercapacitor is treated as a device with a million times or higher capacitance, they can be used in different applications, such as high-efficiency linear DC-DC converters, surge absorbers, LED lighting systems and inverters with completely new design approaches. These supercapacitor-assisted (SCA) techniques use the two essential properties of an ideal supercapacitor, (i) very long time constant and/or (ii) performing as lossless voltage droppers. This paper presents a summary of Supercapacitor Assisted Loss Management (SCALoM), as the underlying basis for high-efficiency converters and protection systems, such as the SCA low dropout (SCALDO) regulator, SCA surge absorber (SCASA) and others. An important property of SCALDO is high efficiency at a very low frequency with DC UPS capability. SCASA is a high-performance surge absorber with less component count than traditional protectors and with higher endurance to repeated high surges, adhering to UL 1449 (3rd Edition) test procedure. The paper will also show how SCALoM concept could be generally used in converters useful in renewable energy systems.

## **INTRODUCTION**

Over the last two decades, electronics industry has seen a new capacitor family, now identified as supercapacitors (SC), which can be practically explained as having one million times larger capacitance for the same canister size. These devices are manufactured by more than 100 manufacturers worldwide, and some of the traditional capacitor manufacturers also have now started manufacturing these, where capacitance per single cell can be in the range of fractional farads to over 100 000 F. These commercial devices can be divided into four categories (i) symmetrical form traditional devices, (ii) hybrid form with one electrode similar to a Li battery, (iii) battery-capacitors and (iv) lithium supercapacitors [1]. Fig. 1(a) depicts the first three types, in the same canister size and type, providing capacitance values from 3000 F to 40 000 F, with DC voltage ratings from 2.7 to 3.0 V. Fig. 1(b) depicts a lithium SC with a 3.8 V DC rating.

These devices are today used in miscellaneous applications including automotive eco-drive (start-stop) systems, UPS systems, portable devices and renewable energy systems and the prices keep coming down

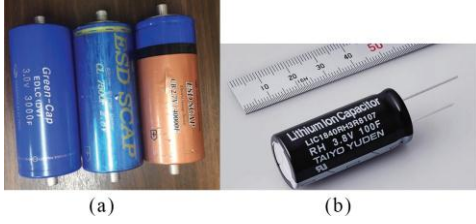


Figure 1: Commercial supercapacitors: (a) large devices in three electro-chemistries; (b) Lithium SCs

rapidly [2,3]. Table 1 provides a price comparison of small supercapacitors useful in some of these applications, with traditional electrolytic capacitors, indicating that they are not too expensive compared to traditional capacitors. Recently Tesla acquired Maxwell Supercapacitors, hinting the wider future use of SCs in the automotive industry.

Table 1: Price comparison of small SCs with similar can size electrolytic devices [4]

canister size (mm)	3-V EDLC (F)	price per 1,000 pieces (US\$)	electrolytic ( $\mu$ F)	price per 1,000 pieces (US\$)
8 × 13	1	0.4	100, 25 V	0.18
10 × 20	5	0.53	470, 35 V	0.24
10 × 30	10	0.6	1, 000, 25 V	0.4
16 × 25	25	1.6	4, 700, 10 V	0.88
18 × 40	50	1.8	470, 50 V	1.7

### SUPERCAPACITOR ASSISTED LOSS MANAGEMENT (SCALoM) CONCEPT

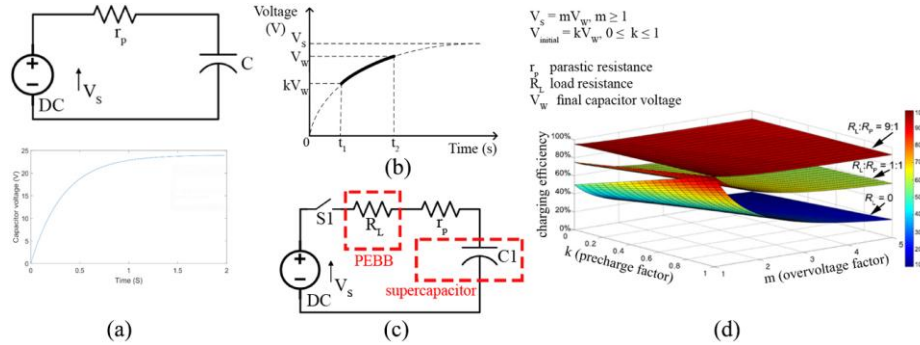


Figure 2: Traditional RC circuit modified to achieve SCALoM theory: (a) traditional RC circuit and the timing diagram; (b) timing diagram for RC circuit with pre-charged capacitor, an over-rated DC supply and a switch; (c) inserting a PEBB (power electronics building block) in place of the resistor in RC circuit; (d) efficiency gains achieved in the SCALoM concept

Referring to Fig. 2(a), when an RC circuit is fed by a DC voltage source, if the capacitor is having zero initial charge, capacitor reaches almost the full DC voltage value within five time constants. The capacitor will store an energy content of  $1/2CV^2$  at the end, while the loop resistance R will dissipate the same amount, provided the capacitor starts from an initial voltage of zero. However, if the capacitor has a maximum rated voltage of  $V_w$ , and if it begins with pre-charge voltage of  $kV_w$  where  $k$  is less than one, case in Fig. 2(b) applies while charging. Here we assume that DC power supply voltage,  $V_s$  is higher than  $V_w$ , initial voltage across the capacitor  $V_{initail}$  is given by  $kV_w$ , and supply voltage  $V_s$  is given by  $mV_w$ , where  $m \geq 1$ . Increased DC source voltage is to allow modifying the basic RC circuit to the new applications discussed later.

Fig. 2(c) depicts how we can modify the simplest circuit in Fig. 2(a) into the case of inserting a useful resistive load  $R_L$  and a very large capacitor (a supercapacitor)  $C1$ . If entire series combination of parasitic resistances (power supply output resistance, supercapacitor ESR, and parasitic loop resistance) is represented by  $r_p$ , where supercapacitor makes it a very long time constant (slow changing) circuit.  $R_L$  could be an added resistor, loaded linear or a switching converter, an LED lamp (DC operable), or even a loaded inverter. We show these in Fig. 2(c) as the power electronics building block (PEBB) in general.

The factor  $m$  comes into the case, since both the supercapacitor and PEBB (in the form of  $R_L$ ) should be kept around nominal voltages, where it helps keep the PEBB operational and the capacitor (when fully charged) also has adequate final voltage to power the PEBB, so that DC source is disconnected from the PEBB during this second phase. During the second phase, accumulated extra charge in capacitor is released to PEBB to keep its connected load operational, while charge balance of the supercapacitor is maintained during the whole cycle.

Detailed analysis (summarized in final paper) as per [5], results in the case of 3-D graphs in Figure 2(d). All in all, by maintaining a ratio of  $(R_L/r_p) \geq 1$  we can reduce the resistive losses in this modified circuit by a huge percentage so that system works with very high efficiency. A detailed discussion of this SCALoM theory is presented in Chapter 9 of Ref [5] and a summary is presented in [4]. A control circuit monitoring the voltage across the PEBB switches the circuit from series case in Fig 2(c) to a case of supercapacitor  $C1$  releases its extra energy into the PEBB to keep it powered (in a parallel configuration), and disconnecting the DC power supply, achieving a efficiency improvement factor of more than 1.

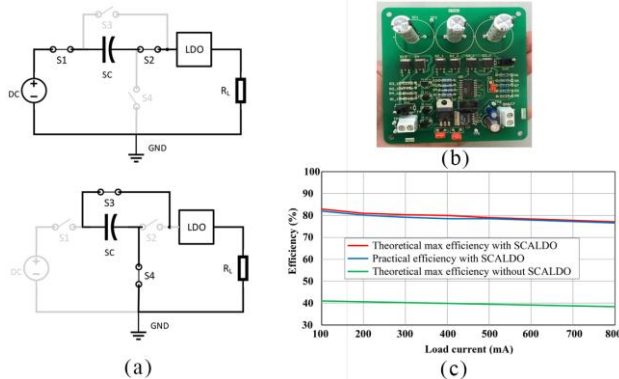
In summary, this concept of SCALoM could be used in a set of novel power converter topologies and protection systems for electronic systems, with useful applications in renewable energy such as the SCA LED technique discussed in [6] and Supercapacitor assisted temperature modification apparatus (SCATMA) in [7].

In the next two sections we show how this new theoretical concept can be used in new power converter topologies such as supercapacitor assisted low dropout regulator (SCALDO) and supercapacitor assisted Surge absorber (SCASA), which culminated US patents [8].

## SCALDO TECHNIQUE AND ITS APPLICATIONS

Traditional DC-DC converter topologies are (i) linear (ii) switch-mode and (iii) switched capacitors versions. Practical power management systems combine them in different ways to build end to end efficiency optimized systems. Compared to switch-modes and switched capacitor converters, which run at high frequencies creating the

need for RFI/ EMI filtering, DC outputs of linear converters are very low noise and they have very high load current slew rate capability. However, when the input to output voltage difference becomes very large, they become very



**Figure 3: SCALDO: (a) the basic concept; (b) 12-5 V implementation; (c) performance curves (84% efficiency with improvement factor of 2)**

inefficient.

Low dropout regulators (LDO), which is a special form of linear regulators solves the efficiency problem by keeping the input to output voltage difference very low. In an LDO where input and output voltages are  $V_{in}$  and  $V_{out}$  respectively, the approximate theoretical efficiency is given by  $V_{out}/V_{in}$ , indicating that they could be very efficient

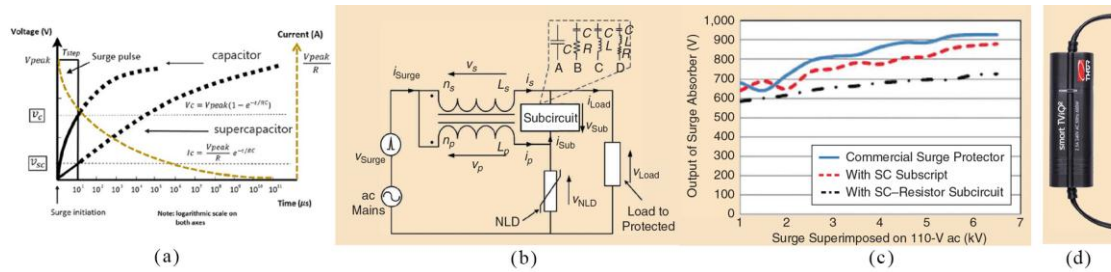
when the series transistor is operating with very low voltage difference.

SCALDO is a uniquely different DC-DC converter technique where an LDO is placed in the modified RC circuit loop shown in Fig. 2(c), depicting the case shown in Fig. 3(a). Now the supercapacitor in upper part of Fig. 3(a) creates a large time constant circuit and the low ESR property of the supercapacitor [4] means that the voltage drop across it is a lossless-drop. The load current of the loaded LDO keeps the supercapacitor charged to its maximum value at which the LDO stops operating as voltage regulator. A control circuit, either analogue or digital could now move the supercapacitor removed from series configuration and then discharge its extra accumulated energy back to LDO in the parallel, keeping the load running continuously. This case is shown in Fig. 3(b) lower part. This SCALDO circuit has the following useful hall marks [9,10]:

- Load sees the high quality RFI/ EMI free output of a linear regulator
- Circuit switches at very low frequency in the range of fractional hertz to milli hertz.
- It can have built in DC-UPS capability within the converter itself, by oversizing the supercapacitor.
- Many different configurations with efficiency improvement factors ranging from 1.33 to 3 is possible.

Fig. 3(b) shows the prototype of a 12-5 V SCALDO converter and Graph in Fig. 3(c) show its efficiency improvement factor of 2. SCALDO has evolved during the last decade and is now being extended to various useful concepts such as dual-output supercapacitor assisted low dropout regulator (DO-SCALDO) [11], reduced-switch SCALDO (RS-SCALDO) [12] and SCALDO extension for the Google server rack which provides battery-less UPS capability within the server rack [10]. More details in the final paper.

## SUPERCAPACITOR ASSISTED SURGE ABSORBER (SCASA) TECHNIQUE



**Figure 4: SCASA technique: (a) simple RC circuit with step DC pulse; (b) SCASA circuit; (c) surge-absorption capability; (d) the commercial implementation [4]**

Another unique application of the SCALOM concept is the SCASA technique, based on the preliminary investigations into the supercapacitors' ability to safely absorb high voltage transient surges [13-16]. Due to the high energy storage capability of supercapacitors, when placed in a resistive charging loop, they create a large time constant circuit. If we apply a momentous high DC voltage to the circuit, such as in lightning-induced voltage on power lines, the capacitor will reach only a nominal DC value, while most energy in the step DC input will be dissipated in the resistive path of the loop. This simple concept is extended into the SCASA technique. Fig. 4(a) depicts this case of a SC in an RC loop where a very short duration high voltage step wave is applied as the input DC source. If the step DC input lasts only microseconds duration, even if the DC voltage of the step is few 1000 volts, the SC will not be charged beyond its rated DC value, while the resistive parts of the charging loop now will dissipate the transient surge energy, without destroying the supercapacitor (mathematical explanation in final paper). However, given that a single cell supercapacitor has a very low DC range in the order 2 to 4 V, it cannot be placed across the live and the neutral of the AC mains, and hence a special circuit configuration as in Fig. 4(b) is required. A detailed description of this is available in [15].

### CONCLUSIONS AND FUTURE WORK

Supercapacitor assisted loss management concept is a very versatile new theory, which has its direct practical applications in many areas of power converters and protection systems useful in portable products and renewable energy systems. SCALoM concept is practically usable since the commercial supercapacitors could be treated as near ideal very large capacitors with minimal series resistance. SCALDO is its most developed set of DC-DC converters, which has the unique property of low switching frequency and hence eliminates RFI/EMI issues. SCASA, shows how it can be used in transient surge protectors. The research team is extending these into many different areas, such as supercapacitor-assisted circuit breakers and supercapacitor-assisted white goods, all adhering to the base concept of SCALoM. Collaboration is welcome in these new areas.

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