High Energy Density Capacitor Storage Systems

Michio Okamura[1]

Introduction

The prospects for capacitor storage systems will be affected greatly by their energy density. An idea of increasing the "effective" energy density of the capacitor storage by 20 times through combining electronic circuits with capacitors was originated in 1992. The method, referred to as ECS (Energy Capacitor System) is now supported by twenty companies and organizations working on actual products. There are two major fields, firstly for vehicles and transportation such as passenger cars, buses, trucks and railroads, and secondly for power lines such as uninterruptible power supplies (UPSs), load-levelers and back up storage for solar or wind-mill generators. Successful capacitor hybrid vehicles have already been described elsewhere [1-4], so this paper will mainly address general applications, including use in power lines.

Capacitor storage difficulty and improvements

There are some inherent problems when dealing with capacitors:

a) Unequal voltage distribution among serially connected capacitors
b) Charge/discharge depth and efficiency are not satisfactory
c) Energy density of capacitors is not large enough

By solving problem a), the storage capacity or effective energy density is increased by more than double with the bonus of added reliability. As well, by improving b), effective energy density is increased by two to three times compared with conventional design. Lastly, c) is related to capacitor designs that can be increased by two to four times depending on their internal resistance. By combining all these factors, an energy density of about eight to twenty-four times the previous 1 Wh/kg level has been attained [2-4].

Serially connected capacitor voltage

Outside of ECS, there are still arguments about problem a) as shown by some differing opinions. One researcher was fortunate enough that no such problem happened and all his capacitors stayed at an almost equal voltage. Others had troubles with unequal voltages and insisted on very tight tolerances for all capacitor cells, for example, matching within 2.5% of capacitance and self-discharge throughout their lives and at the entire range of operating temperature.

When capacitors *C1 ~ Cn* with leakage resistances of *R1 ~ Rn* are connected serially and charged to a total voltage of *V*, the distributed voltage *Vx* to a capacitor *X* will be [2-4],

$$V_X = \left(\frac{k \cdot R_X}{R_1 + \ldots + R_n} + \frac{(1-k) \cdot {}^{1}\!/_{C_X}}{{}^{1}\!/_{C_1} + \ldots + {}^{1}\!/_{C_n}} \right) \cdot V \quad (1)$$

where k varies with time in the range ($0 \le k \le 1$). Internal resistance and serial inductance of capacitors provide no significant effect.
At time $t = 0$, when the capacitors are charged from 0 V, $k = 0$ and the voltage distribution among those capacitors are solely dependent on the variations of capacitance. When the time approaches $t = \infty$, then $k = 1$, and applied voltage will be divided only by their leakage

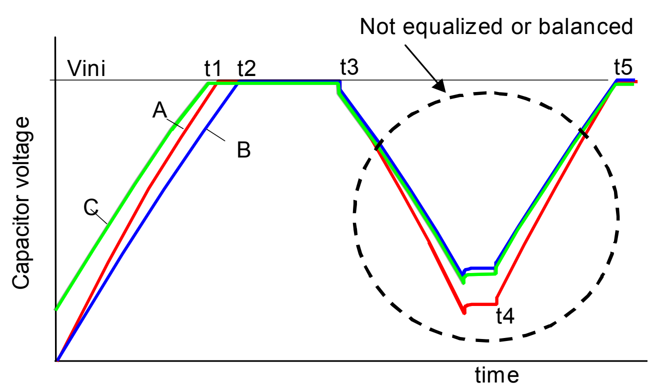

Figure 1: Initialization applied for serially connected capacitors A, B and C

[1] Okamura Lab., Inc. Yokohama, Japan. Email: mitimoku@yhc.att.ne.jp

resistance, unrelated to each capacitance. Every capacitor cell must withstand the highest voltage expressed in equation (1).

Initializing Capacitors

There are ways other than relying on the strictly matched characteristics of capacitors, such as electronically balancing or equalizing capacitor voltages. However, they are neither economical nor efficient, because the circuits are not efficient or always consume energy.

In ECS, all the capacitors are not balanced, and instead are initialized to the same maximum voltage *Vini*. Electronic circuits called parallel monitors, mounted on each serially connected capacitor, will adjust only the charging maximum voltage to *Vini*. No other balancing action is necessary. As a result, the amount of adjusting current for each capacitor will converge to the level of leakage current, which is negligible in terms of energy consumption.

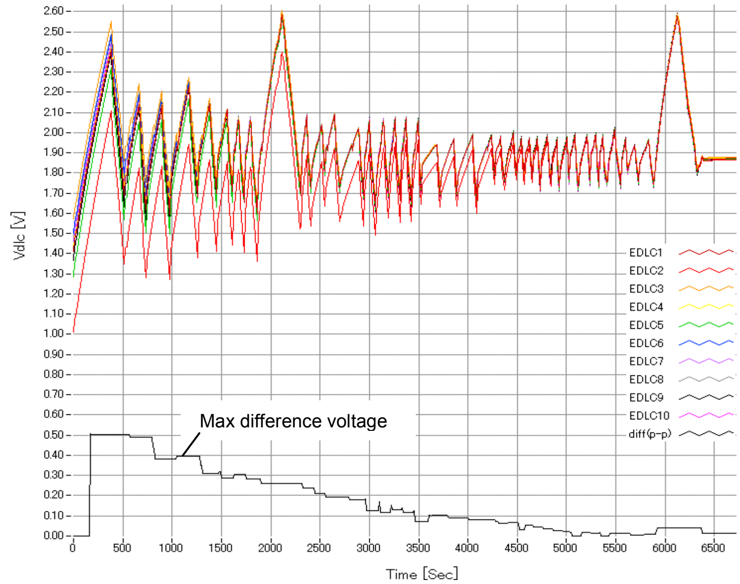

Figure 2: Automatic initialization and the maximum difference voltage decrease

Capacitors are not necessarily initialized at their maximum voltage, but can be done so at any lower voltage or timing by applying the same principle. Waiting for 20 minutes, for example, for initialization after turning on the ignition key, may be rather irritating to drivers, even if the process might be very useful for capacitor utilization. To carry out the process while using or driving, automatic initialization as shown in Figure 2 has been added in the control scheme of parallel monitors.

Limitation of the Maximum Voltage

When capacitors are serially connected without parallel monitors, there are limitations on the useable maximum voltage depending on the statistical dispersion of capacitor characteristics. Larger numbers of capacitors in serial means greater chances of capacitors with larger errors included. Matching two capacitors is an easy matter, but 100 volts becomes risky, and 800 volts may be impractical.

On the contrary, when parallel monitors are employed in ECS, the only limitations for the maximum voltage are the reliability of the electronic parts and insulation of the module containers. There are already numerous examples of 400 to 800 volts serial capacitor banks and even 4 kV to 8 kV ones will be practical when required.

Charging and Discharging Capacitors

When a capacity C with internal serial resistance R is charged from a voltage source V as shown in Figure 3 (a), the charging current i is:

$$i = \frac{V}{R}\exp\left(-\frac{t}{CR}\right) \qquad \text{.......... (2)}$$

The total dissipated power throughout the charge will be:

$$\int_0^\infty i^2 R dt = \frac{1}{2}CV^2 \qquad \text{.......... (3)}$$

This exactly equals the stored energy in the capacitor. Thus, when charging a capacitor from a voltage source or discharging it to a voltage target, the efficiency always settles to 50%.

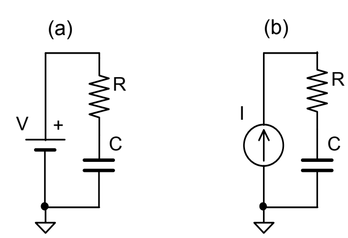

Figure 3: Charging from a voltage (a), or a current source (b)

At constant current I, when charging or discharging a capacitor for t seconds, the amount of charge Q is:

$$Q = I \cdot t \qquad \text{.......... (4)}$$

Meanwhile, the stored energy U will be:

$$U = \frac{1}{2} \cdot \frac{Q^2}{C} \qquad \text{.......... (5)}$$

The loss L in the internal resistance R of the capacitor is:

$$L = I^2 R \cdot t \quad = R \cdot \frac{Q^2}{t} \qquad \text{.......... (6)}$$

Using (5) and (6), the charging efficiency Pc and discharging Pd should be:

$$Pc = U/(U + L) \;= 1/(1 + 2RC/t) \qquad \text{.......... (7)}$$

$$Pd = (U - L)/U \;= 1 - 2RC/t \qquad \text{.......... (8)}$$

Expressions (7) (8) show very important relationships. Because the efficiency is determined not by the absolute value "*R*", but by the relative value "*RC/t*", capacitors with large internal resistance are not always inferior and can be used efficiently. Formulae (7) and (8) also confirm that charging from a current source for a longer time at a smaller current can increase efficiency.

Above results spurred us into two directions of development. Firstly in electronics, to find the methods of producing simple and efficient current sources, because almost all existing power supplies are voltage sources. Secondly, to design capacitors with controlled *RC* or Ohm-farad [1-4] characteristics suitable to specific applications, and utilize larger internal resistance to increase the energy density of capacitors.

Current Pumps and Bank Switching

The simplest way to convert a voltage source to a current output is to insert a chopper-type switching converter

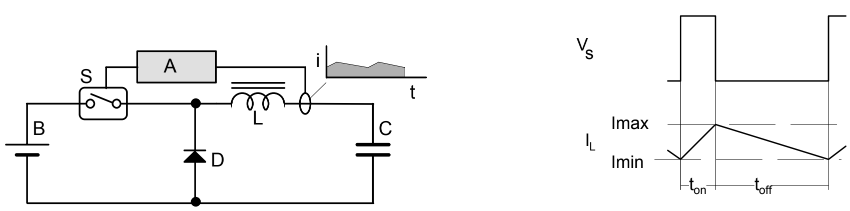

Figure 4: A typical step-down chopper can be applied for a current source, choke current I_L is regulated

between the voltage source and the capacitor to be charged. Though a step-down chopper is shown in Figure 4, three well-known basic chopper configurations provide inherent current sources. Those choppers or current pumps are used as standard parts in all major ECS applications. For example, Shizuki Electric Co., Nishinomiya, Japan started selling their 200 kVA, 100 kVA and 50 kVA UPSs in the domestic market in March 2002. Their 100 kVA system, which incorporates 8 modules of 20 EC-L type cells sustains up to 1 second of full interruption of the power [5].

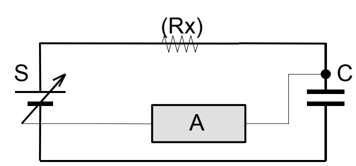

Figure 5: voltage controlled current source

There is another technique to synthesize the current source by controlling the output voltage of the voltage source. As shown in Figure 5, by adjusting the source voltage *Vs* to always be a little higher than the capacitor voltage *Vc*, a voltage controlled current source can be obtained. This is a useful way applicable to any controllable voltage power supply including generators and rectified power supplies.

By combining the above two schemes, a practical method of "bank switching" was developed. All the capacitors are serially connected as in Figure 6 (d) at the start of charging, and are switched to partially parallel (c) and to (b) along with the voltage rise of capacitors. The voltage trace shows up as a saw-tooth shape where the voltage

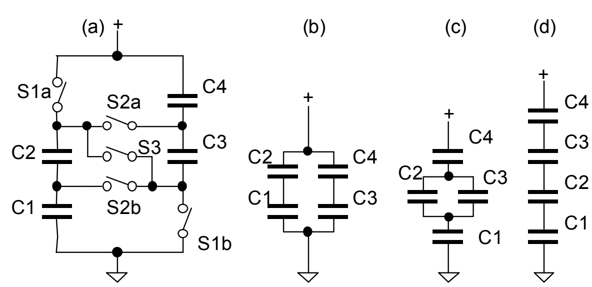

Figure 6: Capacitor bank switching configuration

variation can be controlled within a certain limited range, for example, within ±15% as in Figure 7.

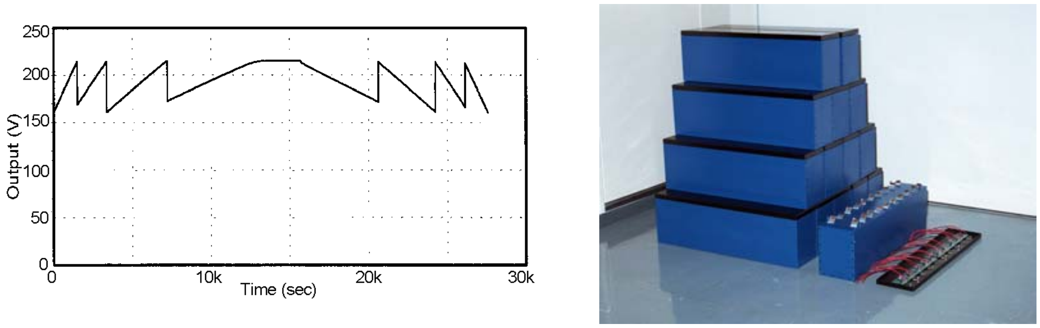

Figure 7: Each 180 Wh/12 L module contains ten EC-B, 18 kF, 1 L capacitors and top mounted parallel monitors [6]. An output voltage plot [6] of bank switching from the rated discharged level, to fully charged, rested for a while and to fully discharged state.

The output of the bank switch may usually be connected to loads such as a motor driver or a DC to AC inverter that can easily be designed to operate in a current mode for those limited ranges. With this combined design, especially for a high power system, a heavy and bulky choke coil together with entire loss of the switching converter is eliminated. An application example shown in Figure 7 is a 5.8 kWh capacitor power storage system employing 380 cells of 1 L 18kF and bank switching ECS [6].

ECS Capacitor design

For ECS, capacitors should also be designed differently. Capacitors do not need to withstand unexpected surge voltages because the parallel monitors control the voltage peak. More significantly, capacitors do not need to have the lowest possible internal resistance as shown by expressions (7) and (8). Rather, they should be designed according to the purpose, or more precisely, depending on the expected shortest charge/discharge time.

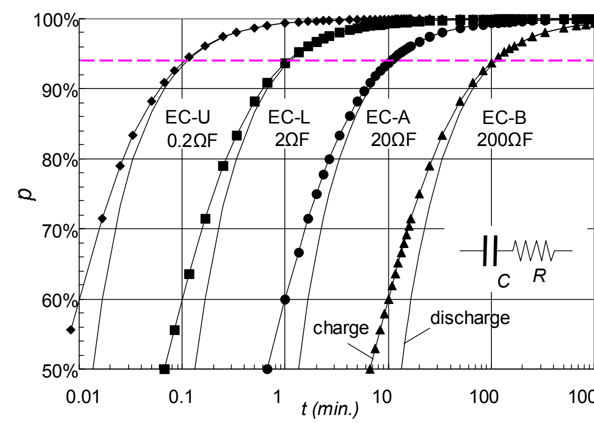

Figure 8: Four capacitors of ten times different internal resistances are plotted on efficiency p, and charging/discharging time t [3,4]

Four capacitors of different ΩF values, namely models EC-U, EC-L, EC-A and EC-B are plotted in Figure 8 by charge/discharge efficiency versus time for full voltage span with a constant current. As clearly shown and proven by equation (7) and (8), each plot is a simple horizontal shift of the other. The charge/discharge efficiency is determined by not the absolute value of *R*, but by the ratio of *RC* and *t* as mentioned earlier.
In the ECS capacitor map shown in Figure 9, the normalized internal resistance, ΩF (ohms for a farad), is fixed as a standard design. The double-scaled X-axis defines internal resistance in ΩF, and the recommendable minimum charge/discharge time at about 94% efficiency.

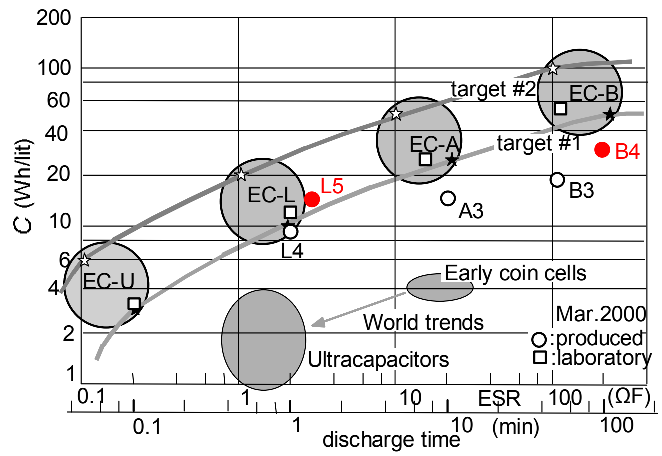

Figure 9: Capacitor map showing energy density vs. internal resistance[3,4]
L5 and B4 are scheduled for 2003

The four circles in the figure are standard ECS type names. EC-L 2 ΩF, suitable for 1-minute

charge/discharge, is intended for hybrid vehicles and uninterruptible power supplies (UPSs).
EC-A type 20 ΩF has a 10-minute duration for general applications. The EC-B type is for durations over 100 minutes and has been applied to load leveling with the highest energy density. Various capacitors of large or controlled internal resistance have been manufactured. Their status is identified as either "research" or "production" by the indications in Figure 9.

Three of those cells are shown in the picture. The cylindrical cell on the left, approximately equal to the "D" size of a dry cell battery is 470 F, five times larger than de facto standard 100 F. This is not because the manufacturing technique is superior, but rather because its internal resistance is allowed to be 20 ΩF instead of 2 ΩF. This is a good illustration that allowing a larger internal resistance can increase energy density. The square cell in the center is a 150 mL EC-L type 2 ΩF 6.5 Wh/kg, or about 10Wh/L with power density of 5.9 kW/kg. At right, a 1 L EC-B type 100 ΩF 12 Wh/kg or 16 Wh/L.

Figure 10: Samples of ECS capacitors [3,4]

Table 1 indicates more detailed specifications for two of the three typical ECS capacitors shown in Figure 10. Work is currently going on to improve energy density by a factor of 1.5 with pure EDLC structure, indicated in the table as "$\rightarrow$ (10)" and in Figure 9.

ECS does not exclude the possibility of pseudo capacitors or other electro-chemical capacitors in principle, but up to now all the ECS capacitors have been pure EDLC that avoid using acetonitrile electrolyte.

Table 1: Capacitor specifications of Power System Co. products in 1999 [4]

Model	PSLP-H2A (EC-L)	PSBP-H3N (EC-B)
Size (mm)	120*105*12 (0.15 L)	125*160*52(1.04 L)
Weight (g)	210	1500
Capacity (F)	1350 (1.35 kF)	18000 (18 kF)
Max. Volt. Continuous (V)	2.7	2.7
Internal Resistance (mΩ)	1.5	5.5
ESR (ΩF)	2.0	100
Energy Density (Wh/kg)	6.5 $\rightarrow$ (10)	12 $\rightarrow$ (21)
Energy Density (Wh/L)	9.1 $\rightarrow$ (14)	17 $\rightarrow$ (30)
Power density* (kW/kg)	5.9	0.22
Power density* (kW/L)	8.2	0.31

* At the matched impedance condition
** Modules are made to order. Allow about 20% increase weight and size

Target applications

In the field of vehicles and transportation, ECS capacitor hybrid cars such as buses, trucks and fuel-cell vehicles have already been completed or will be soon put on the market [7,8]. Also in this field, though it is not certain, there will be possible applications of an ISG/42-volts system and an idling stop. Those applications will contribute to increasing the production quantity of capacitors and hence the cost per watt-hour will decrease.

In the power line area, demand for high power density EC-L type has arisen first of all because there is no direct competition with batteries for those high power applications. As mentioned earlier, ECS capacitor UPSs of 50 kVA to 200 kVA shown in Figure 11 (a), have sufficient merits and that is the reason why they are being sold as commercial products in the Japanese market. Other than UPSs, there are various applications for EC-L type capacitors in that area, such as peak load leveling for co-generative stations, fuel-cell systems and power line stabilization.

Though the EC-B type has achieved the highest energy density among pure EDLCs, it is not as competitive with various batteries as the high-powered EC-L type. This is due to the fact that the EC-L

Table 2: Comparison of storage technique, practically used or under development [6]

Storage types	Efficiency (AC-AC)	System scale	Remarks
ECS capacitors	84%	1kW*4h	Weekly efficiency DC-DC 94%
NaS batteries	76%	2000kW*8h	Weekly efficiency
Redox flow batteries	72%	450kW*2h	Weekly efficiency
Lead acid batteries	78%	30kW*4h	Weekly efficiency DC-DC 86%
Superconductive flywheel	53%	0.3kWh	Charge 2190sec, discharge 1120sec, no standby time
Pumping station	≈ 70%	Practical use	Weekly efficiency (≈daily efficiency)

type has almost no competition in terms of its high power density, but the EC-B must compete with batteries according to the price per watt-hour. In terms of energy density, batteries still maintain a much better position and are produced in a larger quantity at a lower price.
Even so, there are many advantages in using capacitors. As shown in Table 2, results reported from the study of an experimental 5.8 kWh (4.0 kWh net output) capacitor storage station shown in Figure 11 (b) [6], numerous features of capacitor storage such as higher efficiency, longer life, lower environmental effects, minimal maintenance and safety characteristics must be evaluated.

Capacitors, as an electrical storage device with such high efficiency and long life should be recognized more highly than solar cells and windmills. Power generation using natural energy is supported world wide since it is easy to understand. However, a good storage system can be more useful in cases because the storage can supply energy to the required location at the timing when it is really needed.
The needed storage systems do not necessarily have to be capacitors, but considering their efficiency, life, safety, small environmental load and scalability, the capacitor storage system is the best candidate.

Figure 11 (a): 100 kVA capacitor UPS by Shizuki Electric Co [5]. b): EC-B 5.8 kWh load leveler 1 kW*4 hrs by Power Systems Co [6].

Conclusion

Power line application of capacitor storage systems, as with vehicle application, has now been made possible by high power density capacitor systems.
Electrical storage that has high efficiency and long life is sometimes more desirable than, or may be interchangeable with power generation. As well, power generation from solar cells or windmills is not reliable. In contrast, the electric energy stored in capacitors can be used reliably for important applications at the required time. The production cost of ECS capacitors should not be high, since there is neither special material nor expensive process used. The reason for the present high price of capacitors is only due to the current low levels of production. If an amount equivalent to the budget for a hydraulic pumping station were to be spent on capacitors, the capacitor cost would drop to a level that is competitive with the station and this would open a wide range of applications.

References

[1] M. Okamura: “A New Capacitor-Electronics Power Storage”, Proc. of EVS-13, 6H-01 (1996)
[2] M. Okamura, H. Hasuike, M. Yamagishi and S. Araki: “A Status Report on the Power Storage System of Capacitor-Electronics” Electrochemistry, Vol.69, No.6 (2001)
[3] M. Okamura: “A Progress Report of the Capacitor Hybrid System--ECS” EVS-18, 5D (2001)
[4] M. Okamura and H. Nakamura: “Energy Capacitor System - Part 1 and 2: Capacitors and their Control” The 11th international seminar on double layer capacitors and similar energy storage devices. Dec.3-5 (2001)
[5] Shizuki Electric Co., Inc., private communication. (2002)
[6] NEDO: “Demonstration Program to Verify New Load Leveling Technologies”, March (2000)
[7] M. Sasaki, I. Notsu, Y. Yamada and H. Kanno, Jidosha-Gijutsu-kai, 20005215, (in Japanese), May (2000)
[8] Honda Motor Co., Ltd., Press Information, Ref. # 00030, Sept. 28 (2000)