SELF-ADAPTIVE SWITCHED ULTRA-CAPACITORS: A NEW CONCEPT FOR EFFICIENT ENERGY HARVESTING AND STORAGE

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Abstract: This paper reports the design, implementation, and testing of an adaptive self-switched array of ultra-capacitors (UC). The purpose of this innovative system is to efficiently store harvested energy to power a wireless and battery-free Wireless Sensor Network (WSN). An optimized control allows improving the energy transfer from a voltage source as well as the energy utilization ratio, hence extending the energy autonomy of such systems.

Keywords: energy harvesting, energy storage, ultra-capacitors, self-adaptive, autonomous systems

INTRODUCTION

The development of wireless sensor networks (WSN) and associated technologies is raising a growing interest for autonomous embedded systems, in a wide range of fields. The wireless nature of such networks implies that each node be energy autonomous, which in many cases, requires harvesting energy from its environment. In most applications, energy storage is also needed in order to provide sufficiently high power and/or autonomy.

Lifetime, ease of use and safety are concerns that may lead to prefer ultra-capacitors instead of electrochemical batteries. However, the main drawbacks are a weaker energy density, as well as a strong dependency between voltage and state of charge. The latter means that a single storage element cannot support long autonomy and fast startup at the same time.

The architecture proposed in this paper aims at addressing this problem by splitting the capacitance into smaller cells, which interconnect according to the amount of energy stored.

The first part of this paper introduces the principle [1] employed by such architecture, as well as simulation results. The second part contains a theoretical analysis for an optimal realization, while the third part presents the implementation and experimental validation of the proposed circuit.

PRINCIPLE

In the context of ambient energy harvesting, the use of adaptive topologies for energy storage is not new [2-5], however existing methods sometimes suffer from charge transfer between capacitors [2,3] as the topology shifts, which induces important losses in parasitic series resistances. Moreover, these structures often address only one phase (either charge [3] or discharge [4]) thus reducing the impact on the energy storage stage global performance. It is nevertheless interesting to note that some work [5] deal with much higher energy levels, which illustrates the scalability featured by this kind of architecture.

The proposed principle [1] is based on the use of a (ultra-) capacitors matrix, which arranges itself according to the global amount of energy stored. This structure shifts from an *all-series* to an *all-parallel* arrangement with discrete intermediate steps, the cycle being reversible whatever the current state (see Fig. 1). Switches are used to modify the capacitors interconnections, and since all successive topologies prevent from any charge transfer between capacitors, no energy is lost at switching events. It is worth mentioning that, at least in principle, this concept is applicable whatever the energy levels or the capacitance values.

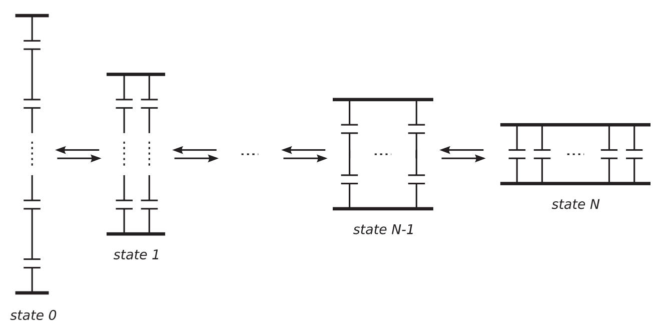

Fig. 1: successive arrangements of elementary capacitors, from the smallest equivalent value (state 0) to the maximum equivalent capacitance (state N).

In order to illustrate this principle, we consider a scenario where, for a matter of simplicity, charge and discharge of the capacitors are separate phases.

Charge – focus on energy transfer

Initially all capacitors are empty and the structure is in ‘state 0’. Since all capacitors are stacked in series, the equivalent capacitance is at its lowest value and lets the voltage across the whole stack increase rapidly. As soon as this voltage meets a predefined threshold, the structure shifts from a single branch to two branches in parallel ('state 1'). As a consequence, the equivalent capacitance increases fourfold as well as the time constant, while the voltage across it is divided by two. This sequence may be repeated until all capacitors are in parallel ('state N').

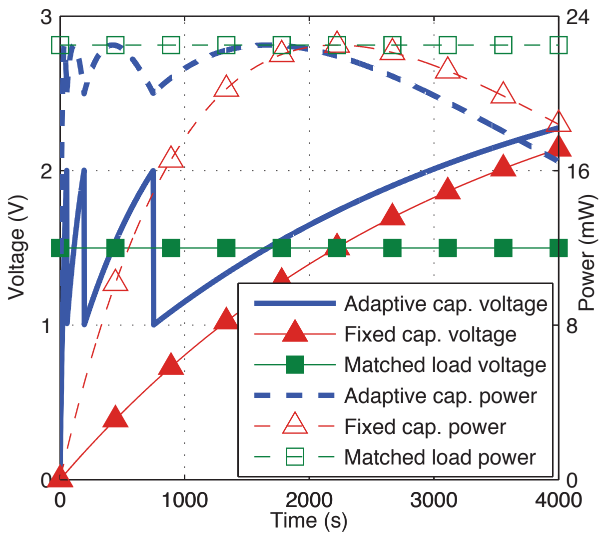

Fig. 2: evolution of charge voltage and power vs. time

Figure 2 shows the evolution of the voltage as well as the instantaneous power stored by the matrix when charged by a Thévenin voltage source. These plots may be compared to those of the "fixed-value capacitance" case together with the load-matching case. It can be seen that the voltage across the adaptive matrix increases quickly and oscillates around the matched-load constant voltage. On the other hand, the incoming power raises rapidly and is kept very close to the maximum power through the successive upshifting events.

Moreover, energy transfer from the voltage source is increased as a result of the load matching improvement.

Discharge – focus on energy utilization ratio

When discharging, the voltage decreases until a second predefined threshold is met. The adaptive structure then shifts back progressively until all elements are in series. Figure 3 shows that this allows to delay the voltage drop across the entire capacitor bank, thus increasing the autonomy of a wireless sensor node.

Indeed, the regulator connected after the storage unit stops working as soon as its input voltage drops below a given threshold V_{min}, which sets a limit on the ratio between useful energy and stored energy.

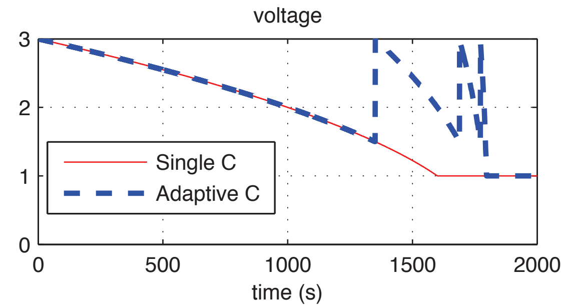

Fig. 3: evolution of discharge voltage vs. time (V_{min}=1V)

This ratio is actually given by:

$$\tau_0 = \frac{W_{useful}}{W_{stored}} = 1 - \left(\frac{V_{\min}}{V_{\max}}\right)^2 \qquad (1)$$

where V_{max} is the maximum voltage across the storage unit. On the other hand, an adaptive structure comprising 2^N capacitors yields the following ratio:

$$\tau_N = \frac{W_{useful}}{W_{stored}} = 1 - \frac{1}{4^N}\left(\frac{V_{\min}}{V_{\max}}\right)^2 \qquad (2)$$

This clearly shows that splitting the main capacitance into smaller elements improves the energy utilization ratio, and therefore increases autonomy.

SELF-ADAPTIVE SYSTEM

This part introduces the basic cell implementation and its generalization towards a generic architecture. The design of the control block is also presented, along with a method allowing optimal operation.

Basic cell

The basic building block of the capacitor matrix is comprised of two elementary capacitors having the same value, and three switches intended to shift from a topology to another.

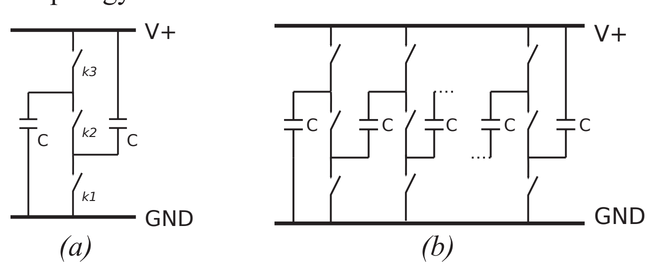

Fig. 4: schematic of the basic cell (a) and the generic architecture (b)

According to the state of switches k_1, k_2, k_3 (see Fig. 4a), the capacitors:

- are in series, and the equivalent capacitance is C/2 (k_1, k_3 open, k_2 closed)
- are in parallel, and the equivalent capacitance is 2*C (k_1, k_3 closed, k_2 open)

As the topology shifts, the basic cell allows a four-fold capacitance shift, and as a result, a two fold voltage shift, while no charge is transferred at a switching event.

Generic architecture

Whereas the basic cell represents the capacitor matrix at order 1, it is possible to generalize it to a higher N^{th} order (Fig. 4b). The order N indicates the degree of discretization of the total capacitance. Such a structure exhibits the following characteristics:

- elementary capacitors count = 2^N ;
- distinct states count = N+1;
- capacitance swing range $C_{max}/C_{min} = 4^N$;
- switches count = $3*(2^N-1)$.

The complexity of this structure exponentially increases with N, as well as conduction losses through the switches. Moreover, choosing an order greater than 2 or 3 brings very little additional gain (Fig. 5). Consequently, there exists an optimal order, which naturally depends on the switches properties as well as the power consumption of the control unit.

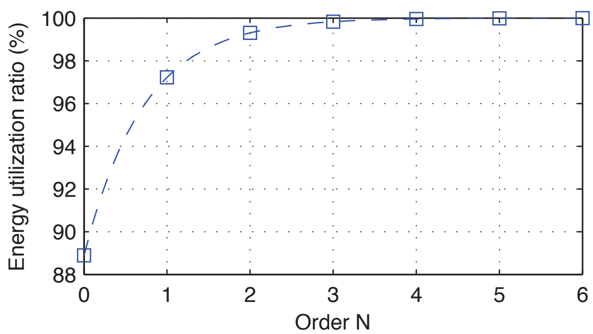

Fig. 5: Energy utilization ratio vs. order N, according to equation 2 (assuming V_{min}/V_{max}=1/3).

Self-adaptive operation

Basically, the storage subsystem is inserted in an energy chain connecting a source to a load (see fig. 6). It is assumed that the converter preceeding the storage subsytem provides a regulated voltage E. When ultracapacitors are employed, it may be desirable that this voltage be close to their maximum voltage in order to ensure their protection and store as much energy as possible. Furthermore, the energy storage stage is followed by DC/DC converter which sets a minimum operating voltage Vmin, as stated earlier.

The structure shifts as the energy stored reaches a given level. Practically, such event can be detected by comparing the charge voltage with internally defined thresholds. Schmitt triggers are used to perform this comparison and feed logical signals to a sequential logic control circuit (see fig. 7), which controls the switches according to the current state and detected events.

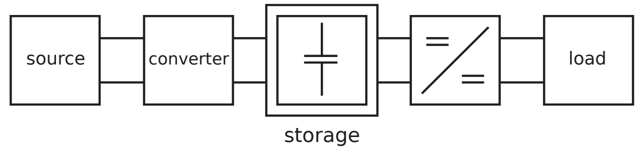

Fig. 6: functional architecture of an autonomous system

Two thresholds are necessary: one is used for charge (V_H) and the other one (V_L) for discharge. These can be defined thanks to an internal reference, or with the knowledge (or measure) of the preceeding converter open-circuit voltage.

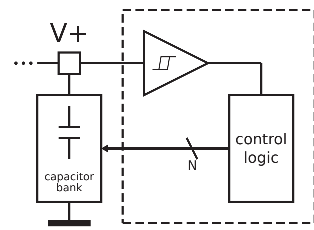

Fig. 7: block schematic of the control circuit

Optimal control

In the case where the energy source can be modeled as a voltage source with emf E, one can analytically determine the existence of an optimal threshold $V_{H,opt}$ which maximizes energy transfer from the source to the storage capacitors:

$$V_{H,opt} = \frac{2}{3}E \tag{3}$$

At each subsequent state, the same reasoning can be applied, such that the optimal threshold remains the same. However, the discharge threshold V_L has less impact, but should nevertheless be greater than V_{min}. Moreover, choosing $V_L < V_H/2$ allows overcoming phenomena that might make the control more complex.

EXPERIMENTAL VALIDATION

A prototype comprising 8 ultra-capacitors (N=3) has been built. It makes use of analog switches with a 025Ω typical R_{ON}. The control logic has been implemented onto a CPLD. The proposed architecture has been tested both in charge and discharge, and compared to an equivalent ultra-capacitor with a fixed value. Experimental results are also compared with simulation data.

Charge

The energy source is a voltage source with emf E=5.5V and 1kΩ series resistance. Figure 8 shows a good agreement between the model and obtained results. Especially, it confirms that the self-adaptive structure reaches a useful voltage level much faster; moreover, the voltage across the capacitors bank is equal to 1.9V as it reaches its last state, whereas the fixed-value ultra-capacitor is charged to 1.24V. This corresponds to 28% more energy stored during the same amount of time, thus also validating the energy transfer improvement.

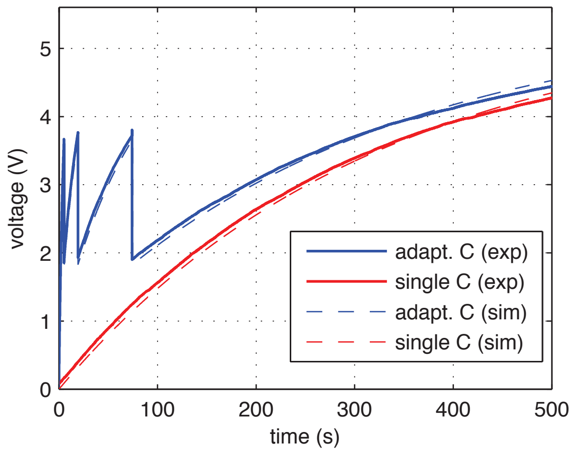

Fig. 8: Charge voltage for a fixed capacitor (a) and an adaptive capacitor (b)

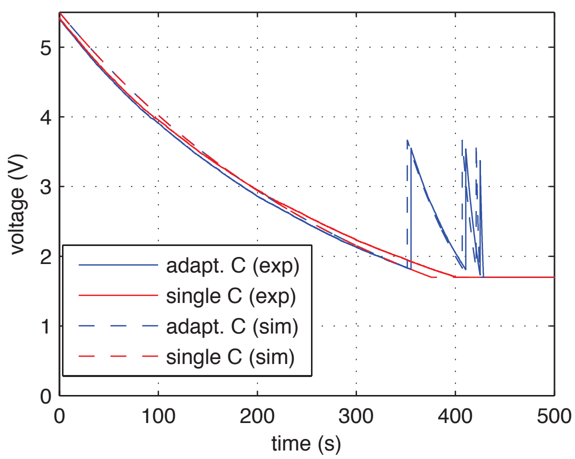

Fig. 9: Discharge voltage for a fixed capacitor (a) and an adaptive capacitor (b)

Discharge

Discharge is done onto a simple 1kΩ resistance. A DC/DC converter with a minimum input voltage V_{min}=1.7V has been emulated. Experimental results (see fig. 9) are again well correlated to the simulated behavior. It can be observed that the fixed-value capacitor provides autonomy of 375s, whereas the adaptive version raises this figure to 425s, which represents a 13% improvement.

Besides, it must be noted that the simulation model uses perfect switches (R_{ON}=0Ω) and perfect capacitors (0Ω ESR). The good agreement between this model and experimental results leads us to the conclusion that the multiple parasitic resistances introduced in the adaptive architecture contribute negligibly to the total losses, at least for relatively small currents.

An issue raised by the experiments is that the structure may – temporarily – be found in a forbidden state if the switches are not well synchronized. However, the use of intermediate states with all switches open can overcome this problem.

CONCLUSION

In this paper, we have demonstrated the interest of a new concept of self-adaptive capacitive storage system, which, just like a mechanical gearbox, adapts itself to the amount of energy to be stored. Though introduced in the context of wireless sensor networks, this concept may be transposable to other contexts dealing with higher power levels.

Finally, future work could include the integration of self-adaptive ultra-capacitors on silicon, as such a technology has recently been demonstrated [7].

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