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Self-Adaptive Switched Architecture for Ultra-Capacitors Storage

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Abstract—*Energy autonomy is a major barrier to the deployment of wireless sensors networks in many applications. Ambient energy harvesting and storage is a way to enhance this autonomy. Moreover, in some applications with harsh environment (extreme temperatures) or when a long service lifetime is required, the use of batteries for storage is prohibited. Ultra-capacitor provide in this case a good alternative for a energy storage. This type of storage must comply with the following requirements: a sufficient voltage during the initial charge must be rapidly reached, a significant amount of energy should be stored and the unemployed residual energy must be minimised at discharge. To answer these apparently contradictory criteria, we propose a self-adaptive switched architecture consisting of a matrix of ultra-capacitors. The initial structure (series) allows a small capacitance to be connected to the source of energy (energy harvesting) at charge starting. The ultra-capacitors are then reconfigured. The final architecture (parallel) insures a maximal energy storage. This adaptive architecture enables a trade off between the charge time constant, the maximum voltage, the autonomy of the system and the maximum energy utilization rate.*

Keywords—*Energy harvesting; energy storage; wireless sensor; ultra-capacitors; self-adaptive switched architecture*

I. INTRODUCTION

Energy harvesting is necessary to ensure energy autonomy of networked wireless sensors. Generally, this type of system incorporates a device to store energy, in order to be able to operate in case of intermittent recovery.

The device used for storage, is either a battery or an ultra-capacitor. In some cases the ultra-capacitor is more interesting than batteries. For example in the case of extreme temperatures (in aircraft), or in terms of safety (batteries may cause fire or explode), or to benefit from a lifetime much greater than that of a battery. Moreover the power peak than can be delivered by ultra-capacitors is greatly larger than the battery one. However, ultra-capacitors have three major disadvantages. Firstly, the output voltage varies with the amount of stored energy, preventing the direct supply of a load and therefore asking for a DC-DC regulator. The second disadvantage is relative to start-up with empty ultra-capacitors: enough energy has to be stored

to attain a sufficient voltage to operate the associated electronic system. If a storage of a large amount of energy is needed, the capacitance will be high, and in this case the charge time constant will be high too. If a fast start-up is required, the value of the capacitance will be too small for efficient storage. A compromise must be found between these two constraints. The third disadvantage is that the DC-DC converter stops working below a certain voltage threshold. Thus, during the discharge, a part of the energy stored in the ultra-capacitors cannot be used.

To partially solve these problems, we propose in this paper a self-adaptive architecture of energy storage. We analyze and compare via simulation two different architectures.

II. SELF-ADAPTIVE SWITCHED ARCHITECTURE

The principle of this structure is to use an ultra-capacitor matrix, whose configuration is modified depending on the state of charge of the overall structure (or in practice by monitoring the voltage across an ultra-capacitor connected to ground), from the configuration "all-series" to a configuration "all-parallel", or vice versa with intermediate discrete states. The cycle is reversible at each step (Figure 1), the successive configurations of the elementary capacitors changing the capacity of the adaptive capacitor, from a low value of equivalent capacitance (State 0) to maximum capacitance (State N). Switches are used to change the association of ultra-capacitors.

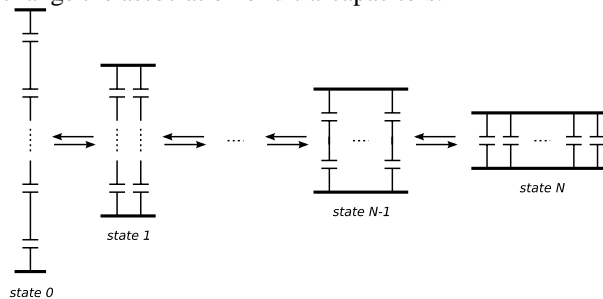


Figure 1: Successive configurations of the self-adaptive architecture [1]

The use of an adaptive topology storage is not new. There are many solutions: one using DC-DC converters [2], another requiring many ultra-capacitors [3], and a third one exhibiting heavy losses due to the number of used switches [4].

Finally, we studied only two structures namely [5][6], which are very similar, and which enable to reduce the startup time and to maximize the stored energy.

A. Presentation of the two self-adaptive architectures

Each of the two self-adaptive structures consists of four capacitors (each has capacitance C). The cells are judiciously interconnected by switches, thus allowing for three configurations. The first one is a configuration « all-series » (S) which allow a fast start by having an equivalent capacitance four times smaller than the final one. Then, when sufficient voltage is reached for proper operation, the architecture moves to a « series-parallel » (SP) configuration, and finally to an « all-parallel » (P) configuration to maximize energy autonomy. The process is reversed towards the SP step and finally the S configuration when discharging the ultra-capacitor to use as much as possible the stored energy.

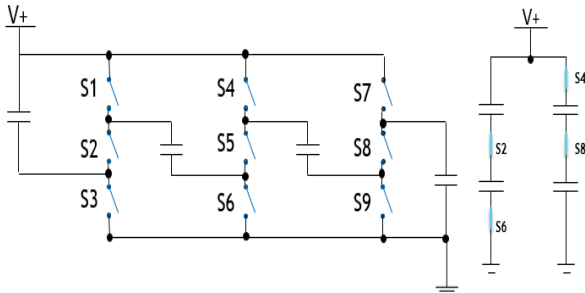


Figure 2: Left part, is the structure of the self-adaptive switched architecture of type I [5]. Right part, is state « SP » of this configuration.

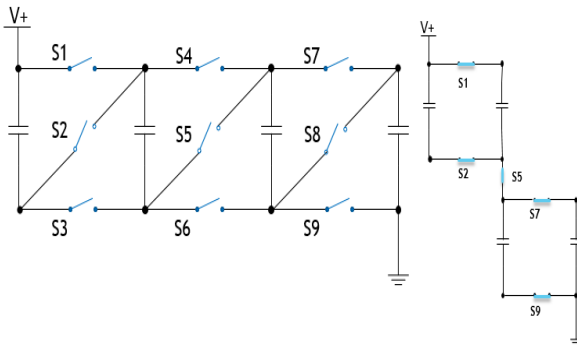


Figure 3: Left part, is the configuration of the self-adaptive switched architecture of type II [6]. Right part, is state « SP » of this configuration.

Both structures, type I [5] and type II [6] present a difference in the SP configuration (right part of Figures 2 and 3). A control circuit allows changing from one configuration to the other. The measured voltage across the overall structure (or the terminals of the last cell connected to ground) is the input of the control logic block, whose outputs are driving the switches

B. Analysis: Ideal system

We have tested the behavior of the system in the case of the combination of 4 elementary ultra-capacitors ($C=50\text{mF}$ for each capacitor).

1) Charge

For this study, a constant power generator supplies the system with a voltage limitation at 3V. The evolution of the

voltage (figure 4) across a self-adaptive matrix is compared with the evolution obtained with two fixed value capacitors, one of low capacity (fast start) and the other of a high capacity (high amount of stored energy).

For the adaptive matrix, the low initial equivalent capacitance value in the configuration (S) allows a very fast voltage rise, then providing a fast start of a sensor network node. The high equivalent capacitance value in configuration (P) on the other hand allows the storage of a large amount of energy.

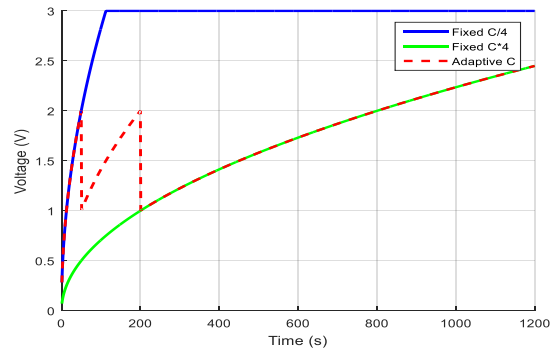


Figure 4: Voltage vs. time for low and high fixed capacitance values, compared to the case of an adaptive scheme, during the charge at constant power.

2) Discharge

Given a load requiring a constant power, during the discharge, successive configurations take place in the opposite order (P configuration to the S configuration). The voltage evolution (figure 5) across the self-adaptive matrix is compared to two fixed ultra-capacitors, during discharge. In this case, the system stops operating at a voltage corresponding to minimum input voltage of DC-DC converter, while a portion of the energy is still stored in the capacitors. On the other hand, in the adaptive structure, the change in configuration minimizes the residual energy in ultra-capacitors and extends the active phase of the DC-DC converter.

It is therefore clear that the use of a matrix of ultra-capacitors allows increasing the utilization rate of stored energy, and therefore the autonomy of the system. However, the use of a high number of ultra-capacitors increases complexity.

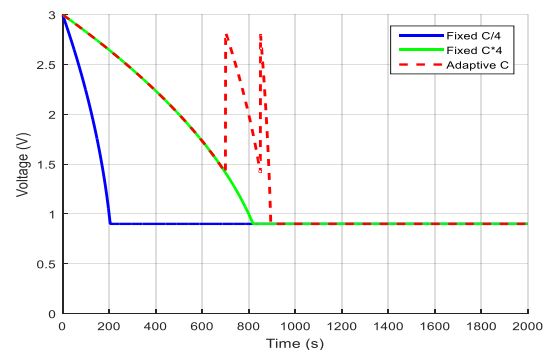


Figure 5: Voltage vs. time for low and high fixed capacitances, compared to the case of an adaptive scheme, during the discharge at constant power.

The self-adaptive switched architecture consequently solves the problems mentioned above (paragraph I) in the case of ideal devices, validating the concept of self-adaptive architecture. However, more realistic simulations are needed.

III. ANALYSIS: REAL SYSTEM

Indeed this self-adaptive architecture, in real conditions, may face the issue of capacitance value discrepancies inducing significant losses, associated to balancing currents. For these simulations, we model each switch by a resistor, and the ultra-capacitor by a resistance (ESR) in series with an ideal capacitor (C).

To evaluate these losses, in a self-adaptive architecture consisting of four ultra-capacitors, we have carried out a study of the impact of the variability of the capacitance value on the maximum losses in each architecture for a given tolerance range (-10% +30%). We found out that to minimize losses, it is necessary to put up the capacitor with the highest value (Cmax) and with the lowest value (Cmin) in the following order: [Cmin Cmin Cmax Cmax] for type I architecture and [Cmin Cmax Cmin Cmax] for type II one. In this case, losses occur mainly during the first configuration switching and not during the second one because voltages equalization has already been realized.

When the ultra-capacitors present some dispersion, there will have a balancing phase during the switching from one configuration to the next, because the voltages will not be identical across the ultra-capacitors. This results in a current peak. In Figures 6 to 9, we present the simulation results of the currents associated to the switching from SP to P. These currents exhibit high values at switching due to balancing currents.

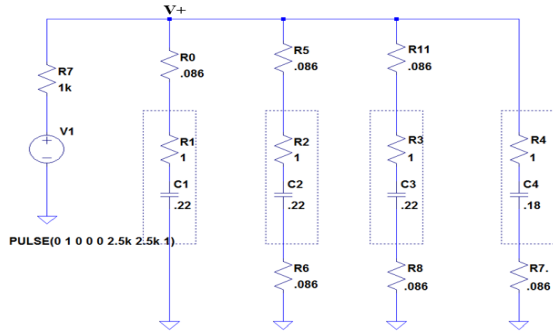


Figure 6: The configuration (P) to the self-adaptive architecture of type I [5]

The analysis of the current peaks (Figures 7 and 9) in each of the structures of types I and II, shows that the second adaptive structure is the best structure. Indeed, the maximum current peak value during switching in the type I self-adaptive architecture, is two times larger than the current flowing in the type II one.

Type II architecture is then preferable in terms of losses. It is simple enough, but to bring a significant gain, it is still needed

to optimize the control part to minimize its complexity and then the losses associated to this driving circuitry.

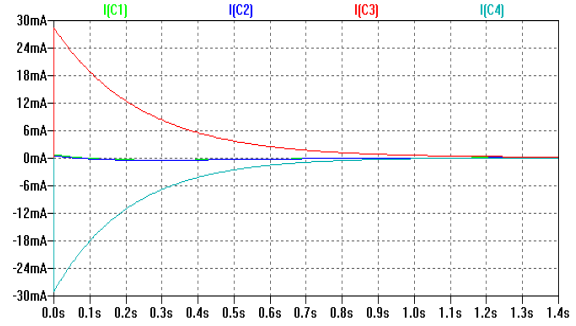


Figure 7: The current peak in ultra-capacitors to the second switch, for the self-adaptive architecture of type I [5]

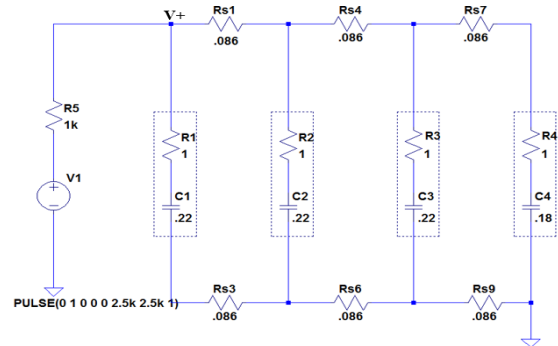


Figure 8: Configuration (P) for the self-adaptive architecture of type II [6]

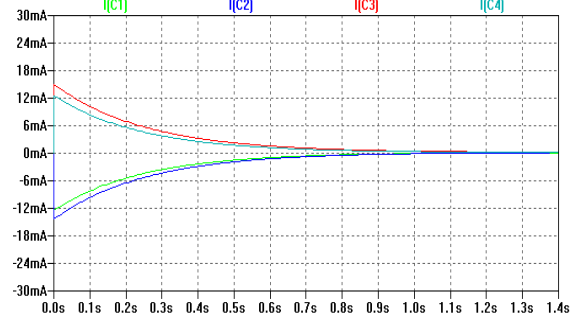


Figure 9: The current peak in ultra-capacitors to the switch, for the second self-adaptive architecture of type II [6]

IV. CONTROL CIRCUITRY

To implement the successive configurations of elementary capacitors, the switches and control logic must be properly designed.

Concerning the switches, we choose CMOS transistors (ADG801), to avoid the presence of the body diodes, which can induce a current path when the switches are in the OFF mode.

From the perspective of control, the solution in type II is much simpler than in type I one, because it uses the voltage of a capacitor connected to ground for triggering switching, and then only requires two comparators and two logic gates (Figure 10). In contrast, type I architecture requires the measurement of

the total voltage of the structure implemented with two comparators, two RS flip-flops and several logic gates.

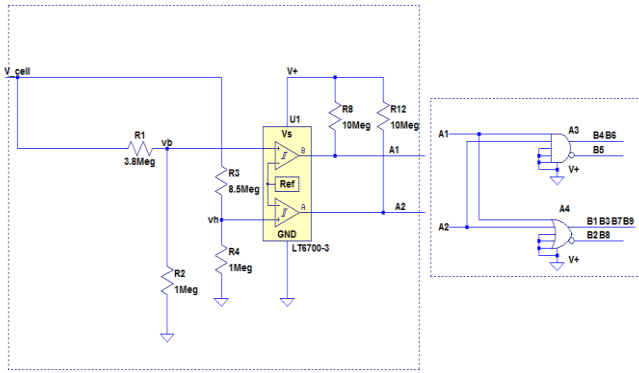


Figure 10: The control logic of the type II self-adaptive architecture

The power supply of the self-adaptive architecture is performed with a voltage source. However, there is a concern about the self-supply of the control circuit when the ultra-capacitors are empty. To solve this problem, we propose to devise an architecture that starts by default in series configuration, allowing its charge without any power supply of the control circuitry. To this aim, several solutions could be considered:

- Using normally-on transistors in normal mode, for the switches that realize the configuration « all series ». This solution is not feasible due to the lack of this type of transistor (PMOS, Depletion P) in the commercial sector.
- Another solution is to use diodes in parallel to the transistors that realize the configuration « all-series », to ensure a good startup until the voltage reaches a sufficient level to supply the control circuit. Once the control circuit is powered, this allows a return to normal configuration cycles. Moreover, to prevent short-circuit during the discharge phase, we should introduce a delay on some switches (S2, S5 and S8) (Figure 3).

V. OPTIMIZED THRESHOLD VOLTAGE

The switching from one configuration to another is done with respect to a comparison between the voltage of the structure (or of a cell) and predetermined voltage thresholds (high and low).

During charge, when the measured charging voltage exceeds the value of the high threshold, the control circuitry changes the topology of the structure towards a higher capacitance value. Similarly, during the discharge of the structure, when the measured voltage reaches the value of the low threshold, the configuration switches to a lower capacitance value.

The choice of the threshold depends of the desired goal (maximizing harvested power [5], high voltage...). To maintain a good behavior of V_h and V_l the thresholds must respect:

$$2V_{\min} < V_h < V_{sc-\max} \quad (1)$$

$$V_{\min} < V_l \quad (2)$$

Where a system stops working below the V_{\min} voltage.

VI. CONCLUSION

In this article, we showed the interest of benefiting from an adaptive capacitive storage device whose equivalent capacitance, similarly to a mechanical gearbox, adapts to the stored energy, optimizing permanently the time constant and the storable energy.

We showed that it was possible to design a self-powered adaptive structure. Future work will be to perform test simulations on software (LTspice), to bring a detailed assessment of losses associated to switches and threshold voltages of the diodes. Later, the construction of two printed circuits (PCB), the first one for adaptive storage structure and the second one, for the control part has to be considered to validate experimentally the simulation results.

In the longer term and for an objective of miniaturization, of the sensor network node, this principle of adaptive ultra-capacitor could be integrated on silicon since the feasibility of integrating ultra-capacitors on silicon has recently been demonstrated [7].

VII. REFERENCE

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VIII. THANKS

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