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Self-Powered Adaptive Switched Architecture Storage

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Abstract. Ambient energy harvesting coupled to storage is a way to improve the autonomy of wireless sensors networks. Moreover, in some applications with harsh environment or when a long service lifetime is required, the use of batteries is prohibited. Ultra-capacitors provide in this case a good alternative for energy storage. Such 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 switched ultra-capacitors. We present the results of a self-powered adaptive prototype that shows the improvement in terms of charge time constant, energy utilization rate and then energy autonomy.

1. 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 cope with ambient energy intermittency. The device used for storage, is either a battery or an ultra-capacitor. In some cases the ultra-capacitor is an interesting alternative to batteries: on the one hand, to benefit from an almost infinite lifetime compared to battery and on the other, in the case of extreme temperatures (in an aircraft, for ex.), to get rid of safety issues. Moreover, ultra-capacitors can deliver much larger power peaks than batteries. 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 requiring a DC-DC regulator. The second disadvantage is relative to start-up with empty ultra-capacitors: enough energy has to be stored to reach a sufficient voltage to operate the associated electronics. If storage of a large amount of energy is needed, the capacitance should be high, and so will be the charge time constant. If a fast start-up is required, the value of the capacitance could 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, part of the stored energy in the ultra-capacitors is lost. To partially solve these problems, we propose in this paper a self-adaptive architecture of energy storage.

2. Self-adaptive switched architecture and prototype

The self-adaptive structure consists of four identical ultra-capacitors (with a capacitance of $C=100\text{mF}$). The cells are judiciously interconnected by switches, thus allowing for three configurations. The first one is a configuration « all-series » (S) which allows a fast start-up 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 storage. 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.

The use of adaptive storage topologies is not new. There are many solutions: one using DC-DC converters [1], another requiring many ultra-capacitors [2], and a third one exhibiting heavy losses due to the number of used switches [3]. This study is carried out within the European project SMARTER [4], dedicated to the development of adaptive storage architecture for a wireless sensor node that is self-powered by piezoelectric energy harvesting. In this project, the whole node will be implemented on a flexible substrate and ultra capacitors integrated onto silicon [4].

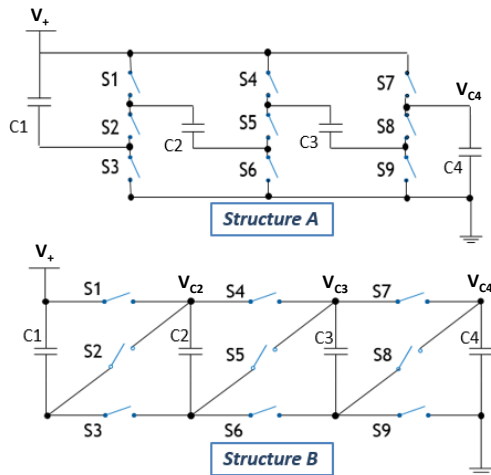


Figure 1. Configuration of the two studied self-adaptive switched architectures.

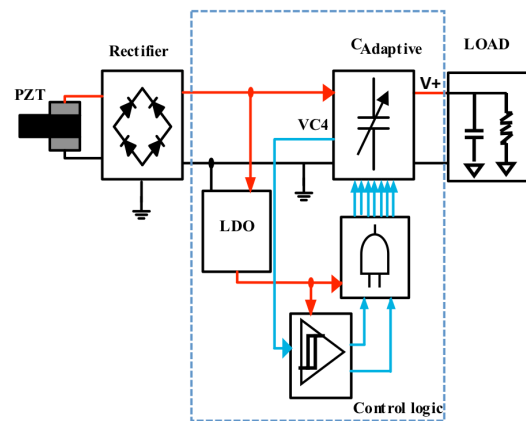


Figure 2. Block diagram of the self-powered adaptive storage architecture.

Two different architectures (Figure 1) have been studied [6][7] and compared with regard to losses to assess if a balancing circuitry is needed. Table 1 summarizes the simulation results, for both structures A and B: it provides the losses related to the variability of the capacitance value for a tolerance range of $\pm 20\%$. We found out that to minimize losses, a judicious placement of the capacitors allows limiting them to an acceptable level and balancing circuitry is then useless. This information is quite important since ultra-capacitors integrated onto silicon could exhibit such large variability. For the implementation of a self-powered adaptive storage prototype, we then used structure B that is slightly more efficient. In addition, this structure has an advantage regarding the associated control circuitry. Instead of monitoring the voltage $V+$ that is applied to the load (see Fig. 1 and 2), the control circuitry only monitors the voltage across the ultracapacitor $C4$ that is connected to ground, assuming that it provides a good image of $V+$ voltage. Compared to the approach of [6] that uses a complex sequential logic, for this latter architecture, a simpler combinational logic can be used that is beneficial in terms of energy consumption.

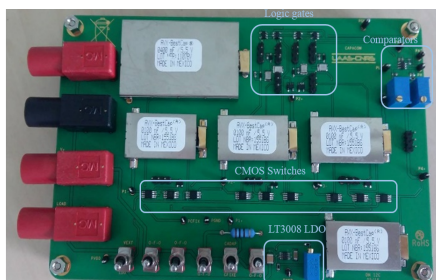


Figure 3. Prototype of the self-powered adaptive storage.

Tolerance range $\pm 20\%$	E_{max} loss (%)	C1 (F)	C2 (F)	C3 (F)	C4 (F)
Structure A	2.08	0.12	0.08	0.08	0.12
Structure B	2.16	0.08	0.08	0.12	0.12

Table 1. Impact of the dispersion in capacitance values on losses (worst case capacitor placement).

A preliminary validation of this concept was already presented [6] but it was not autonomous, i.e. an external power supply was used for the control circuitry. The schematic architecture of the self-powered adaptive storage architecture is given in Figure 2 and was validated using commercial components (Figure 3). The matrix of ultracapacitors is made up of four AVX-BestCap supercapacitors of 100mF that are interconnected by nine ADG801 normally-off CMOS switches. An LT3008 LDO allows powering the control circuitry that is composed of two comparators and four logical gates driving the switches.

The comparison of the charge voltage of the structure (or of a cell) to predetermined voltage thresholds (V_{high} and V_{low}) allows switching from one configuration to another. During the charge, when the measured charging voltage exceeds V_{high} , the control circuitry changes the topology of the structure towards a higher capacitance value. Similarly, during the discharge, when the measured voltage reaches V_{low} , the configuration switches to a lower capacitance value. The choice of the threshold depends on the desired goal (maximizing harvested power [6], high voltage...). For an optimized behavior, V_{high} and V_{low} should respect:

$$2V_{min} < V_{high} < V_{max} \quad \text{and} \quad V_{min} < V_{low} \quad (1)$$

where V_{min} and V_{max} are the minimum and maximum operating voltages of the electronics to supply, respectively.

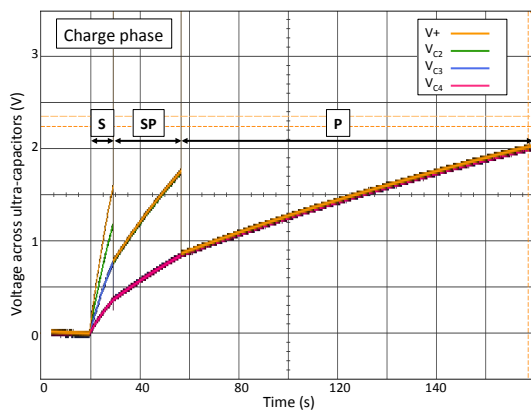


Figure 4. Measurement of the self-adaptive storage prototype in the charge phase. S, SP and P indicate ultra-capacitor configuration: all series, series/parallel and all parallel.

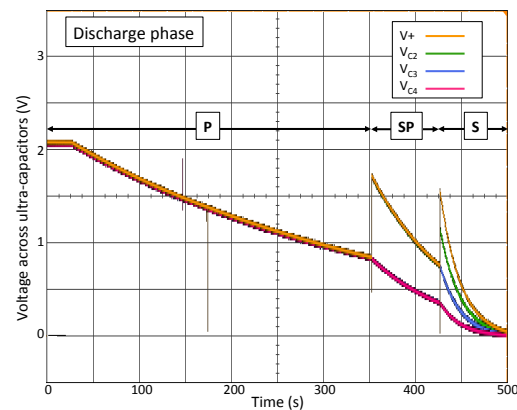


Figure 5. Measurement of the self-adaptive storage prototype in the discharge phase. S, SP and P indicate ultra-capacitor configuration: all series, series/parallel and all parallel.

3. Experimental results

We have tested the proposed architecture. For the charging phase, we used a Thevenin generator made up of 1k Ω resistor and 4.5V voltage source to simulate an energy harvester source. For the discharge phase, we connected a resistive load of 1k Ω between V+ and ground to simulate a constant power load. During these two phases, in addition to V+, we monitored the voltages at each intermediate node (VC4, VC3 and VC2) with reference to ground.

3.1. Charge phase

Figure 4 presents the experimental waveforms obtained during the charging phase. At starting, the ultra-capacitors are empty and they are configured in series (S). This allows reaching very rapidly, in 5 s, the voltage threshold (0.8V) required for operating the electronics. This has to be compared with a configuration with a single storage capacitor that requires a starting time of 55 s. We can notice that voltage V_{C4} used to monitor the switching to another configuration is exactly proportional to one fourth (400 mV) of V+ voltage when switching from S to SP configuration. Then the adaptive storage switches to a series-parallel (SP) configuration and finally to an all parallel (P) one.

We have measured the total energy stored in the adaptive storage and compared it to a single capacitor architecture when the storage element is fully charged up to 4.5V. The losses related to the required control electronics result in 91% energy storage efficiency.

3.2. Discharge phase

Figure 5 depicts the voltage evolution across the self-adaptive matrix during the discharge phase. In this case, the system stops operating at a minimum voltage corresponding to the one required to operate the electronics, while a significant portion of the energy is still stored in the capacitors. Using the adaptive configuration that switches back to SP and finally to S configurations, it is possible to minimize this residual energy. Compared to single storage capacitor architecture, the adaptive approach allows saving 5% of this residual energy, which is in this case, does not completely compensate the energy required to power the control electronics. However, this performance should be greatly improved by moving to a dedicated power-management integrated circuit.

4. Conclusion

We have validated the concept of an adaptive storage for improving the dynamic behaviour of a battery-free storage architecture based on ultra-capacitors. It allows significantly boosting the start-up time and the energy management requires some more optimization to get the full benefits of this approach in terms of energy usage efficiency that an integrated solution should provide.

5. References

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