Hierarchical Hybrid Power Supply Networks

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ABSTRACT

With the advent of newer power supply technologies, power sources with differing energy storage densities and recycling capabilities are becoming available. Combining the power supplies in a hierarchical way would create a unique opportunity for better matching the underlying resources to fluctuating application demands. Such a heterogeneous hybrid network of power supply components could address a variety of power needs and serve a much broader range of system loads with a high efficiency.

Categories and Subject Descriptors

C.4 [**PERFORMANCE OF SYSTEMS**]; B.8.2 [**Performance and Reliability**]: Performance Analysis and Design Aids

General Terms

Algorithm, Design, Performance

Keywords

Power management, hybrid power supply, supercapacitors

1. INTRODUCTION AND MOTIVATION

Historically, almost all elements of computer, communication and embedded systems have evolved from flex structures into rather complex hierarchical networks. At each level of hierarchy, the components have different tradeoffs between two or more performance metrics. As an example, modern processors have a few storage options including data path registers, at least two levels of caches, main DRAM memory, FLASH memory, and external disks. The performance metric for determining the best storage option includes speed of access, size, power, density, and memory permanency. For example, one can access the datapath registers in hundreds of picoseconds, the SRAM-based caches in nanoseconds, the main processor memory in tens of nano seconds, and the external disks in milliseconds. The DRAM access time is about 3 times longer than the SRAM access time, but the DRAM power consumption is typically around six times lower than SRAM power usage. Depending on the task at hand, an interleaved combination of the SRAM or DRAM cells maybe used.

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Property	Supercaps	Capacitors	μFuel Cells	Batteries
Cycle	[10^{-3},1]s	[10^{-9},1]ms	[10,300]hr	[1,10]hr
Life	>30k hr	>100k cycles	1.5-10 khr	150-1500 cycles
Weight	1-2g	1g-10Kg	20g-5kg	1g-10kg
Power ρ	[10,100] kW/kg	[.25,10^4] kW/kg	[.001,.1] kW/kg	[.005,.4] kW/kg
Energy ρ	[1,5] Whr/kg	[.01,.05] Whr/kg	[300,3000] Whr/kg	[8,600] Whr/kg
Pulse Load	Max 100A	Max 1000A	Max 150 mA/cm^2	Max 5A

Table 1: A comparison of power supply properties.

We believe that a confluence of technological and application trends require creation of hierarchical power supply networks consisting of heterogenous power sources. Currently, there are two distinct methods for electrochemical energy storage: (i) In a battery, the charge storage is usually achieved by transferring electrons which generates a reaction in the electro-reactive medium; (ii) In an electric double-layer capacitor, also known as a*supercapacitor*, no electron transfer takes place across the large surface electrode interface. This creates an extraordinary high capacitance with a fast charge cycle.

2. HETEROGENEITY

The heterogenous components in a hierarchical power supply network would include batteries, supercapacitors, ionic supercapacitors, and future emerging components. To make the case more clear, Let us compare the battery and supercapacitors in terms of three common performance metrics: *charge cycle*, *charge density*, and *power density*. In terms of charge cycle, supercapacitors are advantageous relative to the standard chemical batteries since they can be charged/rechaged at a much higher rate. In terms of charge density, the chemical batteries provide a much denser charge storage. The power density metric combines charge density with speed of draining the energy out of device. The overall power density of supercapacitor is much higher than batteries. The emergence of new material and technologies is enabling new hybrid integrated devices comprised of batteries and supercapacitors [5]. Such a device can combine the high charge capacity of conventional batteries with the rapid charging and efficiency of supercapacitors. Table 2 compares the characteristics of four different types of power supplies[1].

In real-world scenarios, the application demands are not fully characterized and there is a need to include heterogeneous power sources [3]. In addition to the inherent differ-

[1] http://www.cap-xx.com

ences in application resource requirements, the same task can have drastically different energy resource requirements during various phases of its execution. It has been shown that under mild assumptions, one can optimally explore the speed-energy trade-off for energy minimization by using different levels of temporal power supplies [2, 1]. There should be an adaptive controller module to estimate the application needs and to accordingly adjust the power resources. To achieve an efficient heterogenous power supply network, one must carefully characterize each power resource. Adaptive online load estimation and optimization methods are required to achieve a better efficiency for the heterogenous power network.

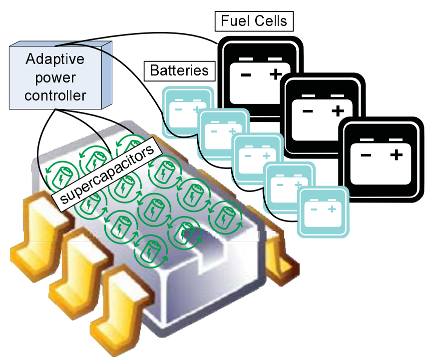

Figure 1: A hierarchical power network consisting of fuel cells, batteries, and supercapacitors.

3. HIERARCHICAL POWER NETWORK

Figure 1 shows the proposed hierarchical network where the top level consists of fuel cell components. The fuel cells in the hierarchy provide permanent and high density energy storage but they are expensive and cumbersome to recharge. Fuel cells differ from the electrochemical batteries since they exploit reactant from an external source that should be constantly provided. The middle level shows one or more batteries and the bottom level shows a large number of supercapacitors. Particularly promising candidates are graphene and cellular based supercapacitors since they have an exceptionally small form factor [5].

Combining few cell batteries and supercapacitors can have significant advantages. Fuel cells, in addition to their high energy densities, have an unlimited lifetime compared with batteries and supercapacitors. During the last decade, system designers started to address the advantages and shortcomings of batteries in at least three different ways. The first one is that the effective energy capacity of the batteries can be drastically improved by slow discharging [6]. The second is that pulsed discharge of batteries can increase the effective battery capacitance by several times by allowing a chemical recovery process. Finally, temperature significantly impacts the effective battery energy capacity. Like electrochemichal batteries, fuel cell efficiency is also dependent on the drawn power (current). Drawing a higher current increases fuel cell's loss and lowers its efficiency.

To show the efficiency of using supercapacitors, we use the widely adopted robot arm controller benchmark from [4] and the task sequences and voltage level benchmark from [6]. Table 2 shows a battery's lifetime improvement by interfacing to supercapacitors. The first row is the benchmark names. The second row represents the battery lifetime and second row shows the lifetime for the battery and a supercapacitor recycling a 50 mA current. We see that the combination has about an average of five times lifetime improvement over a single battery.

	P_1	P_4	P_5	P_6	P_{13}
L_{500mA}	62.3	14.7	57.5	62.4	60.8
L_{50mA}	251.62	144.7	217.12	216.88	299.5
Gain	×4.04	×9.84	×3.78	×3.48	×3.77

Table 2: Comparison of battery lifetimes with and without supercapacitor.

4. IMPACT AND FUTURE DIRECTIONS

Many research questions remain to be addressed before the hybrid power supply networks become a reality. These include characterization of emerging power sources at an appropriate abstraction level, sampling and adaptive optimization for matching power supplies to software and application data, optimized methods for charging and discharging power sources, and optimizing allocation of resources.

The power supply networks are key enablers for new and emerging technologies. Many types of nano- and transistor-based sensors require reset voltages in the range of 10s of volts. Racetrack memories are spin-based nano circuits that have the potential to realize the long-term dream of universal storage because of their ultra small cell sizes and nano seconds access times. However, for utilizing their full potential one may require a voltage in excess of one kilovolts. The only realistic way to create this short-term ultra high-voltage power supply network is by concatenating a significant number of supercapacitors. In addition, the emerging generations of devices are likely to have a significant number of actuators requiring high voltages. Finally, and perhaps most importantly, even for conventional circuits one needs to occasionally provide very high currents. This is to reduce the energy consumption of future generation of ICs, since the most efficient method is to reduce the voltage (quadratic energy savings). However, a very low supply voltage compounded with a large number of capacitive transistors would necessitate a very high power for short intervals of time. This scenario can be effectively handled by ionic supercapacitors.

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