Survey of Supercapacitor’s Application for Power Awareness of Embedded Systems in Internet of Things

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Abstract—The main challenge in designing mobile embedded systems for internet of things is to provide a solution that has the limited power by battery lifetime, in addition to overcome frequent battery recharging or replacement. The help of solar and wind energy harvesting systems is an attractive method to increase the autonomy of mobile embedded systems for internet of things trying to make a continuous operation. In addition, some efficient schemes using supercapacitor based on rolled and stacked type, reconfigurable array, and hybrid storage are designed to maximize the usable energy. Therefore, we find supercapacitor’s tremendous potential to hold a very high charge which can be released in a controlled manner under various applications. Based on this advantage which we focus on, we have surveyed supercapacitor’s application for power awareness in mobile embedded systems for internet of things, its related contents and its future possibility.

Keywords—Internet of Things; Mobile Embedded Systems; Supercapacitor; Rolled and Stacked Type; Reconfigurable Array; Hybrid Storage

I. INTRODUCTION

The interest in supply circuits that collect energy from the surrounding environment for powering embedded systems for internet of things has been increasing in a few years [1], [2], [3], [4]. According to the progress in low-power design, research has greatly reduced the size and the power consumption of mobile embedded systems for internet of things, and the autonomy of these systems can be further increased by energy-aware techniques depending on the use of electro-chemical batteries with various limitations.

As an alternative technology, supercapacitors are high power density, long life, electrical energy storage devices, that exhibit electrical properties, namely charging capability, similar to those of conventional capacitors, and therefore promise an order of magnitude shorter charging cycles comparing with those of conventional batteries [5], [6].

In this aspect, we find an immense possibility of the supercapacitor in terms of the power saving for all kinds of mobile embedded system for internet of things. It resembles a regular capacitor with the exception that it offers very high capacitance in a small size. Supercapacitors are unique in that they are able to combine the energy storage properties of batteries with the power discharge characteristics of capacitors.

In this paper, we have surveyed about power-awareness applications of supercapacitor in mobile embedded systems for internet of things. Especially, we focused on the current mainstream technology and made a comparative analysis between battery and supercapacitor. In addition, based on various backgrounds which is related to the fundamental principle of supercapacitor and their barriers, we caught up in-depth knowledge and it’s perspective for the future work.

The remainder of this report is organized as follows. After Section 2, which presents the Motivation for the Survey, Section 3 will introduce the Background. Then, Representative Models for power-aware design using supercapacitor will be introduced in Section 4. Section 5 will show the Comparative Analysis based on our survey, followed by some Barriers in Section 6. Finally, Section 7 will discuss about the Future Possible Approach and Section 8 will summarize this survey in Conclusion.

II. MOTIVATION FOR THE SURVEY

Our motivation for this survey is to study the possibility to take advantage from supercapacitors in mobile embedded systems for internet of things. At this time, batteries modules are the most popular energy storage system for mobile embedded system due to their high energy density and easier portable applications. However, there are still some problems such as short lifecycle, long recharge time and limited temperature flexibility. For that reason, supercapacitors are an excellent complement to batteries.

In particular, supercapacitor is not subject to the wear and tear of aging experienced by the electrochemical battery with limited cycle and also it enhances pulse current handling by paralleling with an electrochemical battery. Due to the features of supercapacitors, the use of supercapacitors instead of batteries enables to extend the operational life time from tens of months to tens of years [9].
A. Key Point of Interests

This paper focused on power-awareness of supercapacitor for mobile embedded systems for internet of things. Therefore, we tried to survey the current technology and to do a comparative analysis between battery and supercapacitor. Also, we analyzed supercapacitor's background, its barriers and its future possible approach.

Fig. 1 shows major components of typical wearable and sensor network systems for internet of things [12]. Based on our survey, we have checked that the communication component consumes much more power than others, especially the processing component as the next one. Although employing supercapacitors instead of batteries must be beneficial for power-aware design with power harvesting unit, there are important roles for the processing component to save the power, the communication component further. Perhaps one of the most important things to maximize power saving is to parallelize approaches in multiple layers including memory, sensors, and firmware, with minimal performance impact.

III. BACKGROUND

A. Batteries

Batteries are the most widely used energy storage method for mobile devices. There are made by many different type of materials the traditional nickel-cd, advanced nickel-cd, nickel-metal hydride, lithium-ion and lithium-polymer [13]. Batteries have a significant higher energy density than supercapacitor, but they have much lower reversibility and their low power.

B. Supercapacitor

Supercapacitors are electrochemical devices, which stores electrical charges by electrochemical double layer effects. There are three main categories of supercapacitors [14]: (1) pseudo capacitors, (2) electrochemical double layer, and (3) hybrid capacitors. Generally, the differences between these categories are in the materials and principles. Electrochemical double layer stores charge by non-faradaic processes and are usually made on carbon based materials. It has high reversibility and high power densities. On the other hand, pseudo capacitance process can be realized by mean of conducting polymer or metallic oxides based and stores energy by faradic processes. They are less reversible and have higher energy densities but not as much as batteries. Finally hybrid supercapacitors are a combination of double layer and pseudo capacitors, enhancing both, power and energy densities.

Supercapacitors charge-discharge efficiency are very high, and the energy lost through heat during each cycle is relatively small while the energy lost through heat in batteries is much larger, making heat removal more crucial and its extraction costs much higher. The efficiency of supercapacitor depends on the internal equivalent series resistance of the capacitor. This means that the cycle efficiency of batteries is around 80%, and the cycle efficiency of supercapacitors is around 95% [15].

C. Sizing Issue

When sizing the supercapacitor, it is necessary to understand the implications of the various factors that not only affect the capacitor, but will also affect the design of the interface power electronics [18]. These factors affecting the choice of capacitor including the peak capacitor voltage, cost of the cell array, allowable maximum percentage discharge, peak current flowing through the capacitor, capacitor time constant, capacitance per cell, cell voltage, number of cells needed, and mass of the cell array.

D. Maximum Power Point Tracking (MPPT)

MPPT is the method of determining the optimal load based on the condition of the energy harvesting device. There are different goals for different scales of applications. For smaller devices, the goal should be to minimize the MPPT overhead, for large energy harvesting devices, the goal is to maximize the transfer efficiency. MPPT techniques are invented for adjusting the operating point of the solar panel in order to obtain the maximum output power from the Photovoltaics (PV) module. At this time, MPPT methods have been classified into two groups: (1) large-scale PV power systems, generally making use of DSPs or microcontrollers, and (2) small-scale PV power systems, usually without digital controllers [16]. There methods are less accurate, but they are cheaper with an advantageous cost efficiency in PV applications below 50W [17]. A third class of MPPT methods, focused on microscale PV power systems has recently emerged, with the increased interest in harvesting technology. Compared to general industrial PV systems, these approaches focus on the tracking of the maximum power point (MPP) with power consumption of a few milliwatts since the maximal energy drawn from PV modules is very limited due to the small size of the cells.
**IV. REPRESENTATIVE MODELS**

**A. Rolling and Stacking**

Today, there are many types of supercapacitor such as stacked and rolled on the basis of its structure and model. Majority of supercapacitor available in market are rolled type. On the basis of nature of electrolyte it is grouped in two parts such as aqueous and non-aqueous supercapacitor. Apart from this metal oxide based, polymer based, composite material based supercapacitor are available [7], [8].

Rolled type supercapacitor is cylindrical shape which has a disadvantage of poor utilization of available space. It is also high faradic values as compared to stacked type. Generally its terminals are two ends. Developing this type of capacitor is difficult to prepare as compared to stacked type capacitor. Stacked type supercapacitor is rectangular shape assists in maximum utilization of available space.

**B. Reconfigurable Array**

The supercapacitors in the array as a group can be dynamically configured for series or parallel topologies by means of a switch array for not only minimizing leakage of the supercapacitors but also improving the charging speed. Furthermore, this kind of supercapacitor array is modular and can be easily expanded. It normally consists of two phases either charging phase or discharging phase. To address the problems with single supercapacitors, reservoir supercapacitors arrays (RSA) were proposed. In particular, a bootstrap supercapacitor, which has relatively smaller capacitance than that of the primary energy storage element, was used to solve the cold booting problems. It reaches a higher voltage more quickly and makes more of its stored energy available in low-energy cases. Existing techniques charge the RSAs serially, which is good for near-depletion conditions; but since the leakage rate of supercapacitors increases rapidly as they approach their rated capacitance, serial discharging becomes inefficient.

**C. Hybrid**

This is combined approach with both supercapacitors and batteries. The objective of integrating batteries and supercapacitors is to create an energy storage system with the high energy density attributes of a battery and the high power density of a supercapacitor. In essence, the goal is to exploit the advantages of both the devices through supercapacitor hybridization of the two technologies in vehicular power system architecture.

Here battery is connected as the primary energy source and the supercapacitor is connected as the buffer system. It is obvious, when supercapacitor works in conjunction with battery, peak power demand will be supplied by the supercapacitor, while the average power demand will be supplied by the battery. Thus there are no chances of sudden overloading on the battery hence the battery life and efficiency of whole energy storage system can be increased.

**V. COMPARATIVE ANALYSIS**

The primary power source of today’s mobile embedded systems for internet of things depends on batteries at most. Batteries are additionally be a critical limiting factor in the lifetime of these mobile embedded systems. Because of the limited number of recharge cycles and inability to hold full charge for long periods of time, the battery will require replacement after one or two years. Unfortunately, such recurring maintenance cost is likely to become very expensive or prohibitive if it must be done for thousands tiny systems in sensor network of internet of things, which are likely to be difficult or expensive to access after deployment. In both cases above, the battery is the primary limiting factor that prevents from operating more than several years without performance loss. In this situation, supercapacitor is solely solution to store energy for achieving even longer life operation. Supercapacitors have received wide attention recently due to their power density, low equivalent series resistance, and lower leakage current than electrolytics [11]. Fig. 2 compares batteries and supercapacitors available for mobile embedded systems for internet of things [11].

The supercapacitor offers more than half a million charge cycles and a 10 years operational lifetime before the energy capacity is reduced to 80% and internal resistance is doubled, which is the point where half the original capacity is available for a supercapacitor or battery at rated current. The supercapacitor generally has an order of magnitude higher continuous current than a battery, and so when a supercapacitors capacity falls down to 80% and internal resistance doubles, nearly 80% of the original capacity can still be drained as long as the sensor nodes peak current is less than a tenth of the supercapacitors continuous current. For instance, continuous current for the Maxwell medium size capacitance (350F) is greater than 80A, and so when the sensor node draws less than 8A peak current, most of the remaining capacity can be utilized. The supercapacitor is estimated to take 20 years to reach 50% capacity degradation. And also, we can tell that comparing with batteries or fuel cells, conventional capacitors have very high power density, but lower energy density. It means that a conventional capacitor can be charged.
or discharged very quickly and generate a high power, but it cannot storage much energy in unit mass or volume.

VI. Barriers

There are also some barriers of using supercapacitors in mobile devices for internet of things. For normal mobile devices which is usually designed to operate with an input voltage of 3.7V. The requirement leads to two problems of using supercapacitors for this purpose: (1) The first one is low maximum voltage per cell, typically 2.7V and (2) the second one is non-constant voltage across the supercapacitor when it discharges [10].

To achieve higher voltages, several supercapacitors are connected in series. This has some disadvantages. Serial connection reduces the total capacitance, and strings of more than three capacitors require voltage balancing to prevent any cell from going into over-voltage. This is similar to the protection circuit in lithium-ion batteries [11].

These problems can be solved by using two methods which are mentioned in Section 4: (1) stacking and step-down converter or (2) single cell with a step-up converter.

There are also some other barriers. For instance, the amount of energy stored per unit weight is considerably lower than that of an electrochemical battery as shown in Fig. 2. It is also only about 1/10,000th the volumetric energy density of gasoline. The voltage varies with the energy stored. To effectively store and recover energy requires sophisticated electronic control and switching equipment.

VII. Future Possible Approach

Mobile devices in conjunction with supercapacitor that can be charged in minutes could soon be possible thanks to a radical new battery technology. The material in the form of a wafer which has recently created by researchers at Vanderbilt can turn phone casings, car chassis and even structural applications like walls into quick charging batteries [19]. This first prototype stores electricity by assembling electrically charged ions on the surface of a porous material, instead of storing it in chemical reactions the way batteries do. Also, this tiny wafer that could mean you can charge all your gadgets in seconds: superconducting material can take a full charge in a matter of seconds - and is smaller than traditional batteries. As a result, supercapacitors can charge and discharge in minutes, instead of hours, and operate for millions of cycles, instead of thousands of cycles like batteries. In addition, it can integrate energy into the components used to build systems, it opens the door to a whole new world of technological possibilities. The ability to design technologies at the basis of health, entertainment, travel and social communication will not be limited by plugs and external power sources.

VIII. Conclusion

This survey paper represents various power efficient approaches combined with durable energy storage in the form of supercapacitors, which are expected to last for 20 years at non-trivial power levels. As we have expected, supercapacitor also can be used along with battery or fuel cell very effectively by systematic selection of type of supercapacitor. Considering shape and size requirements of target system along with technical specifications, the mobile embedded system designer has to choose a proper type supercapacitor and its application model for the efficiency and reliability of storage.

Although, for the time being, supercapacitors have a relatively low energy density to outdo the present role of the battery, its advantages can, in a near future, change the paradigm of charging mobile embedded systems for internet of things.

REFERENCES