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Super-capacitor and Thin Film Battery Hybrid Energy Storage for Energy Harvesting Applications

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Abstract. This paper presents the design of hybrid energy storage unit (HESU) for energy harvesting applications using super-capacitor and thin film battery (TFB). The power management circuits of this hybrid energy storage unit are proposed to perform "smart" charge/discharge control in order to optimize the HESU from the perspectives of energy loss due to leakage current and equivalent series resistance (ESR). This paper shows the characterizations of ESUs for energy harvesting powered wireless sensor networks (WSN) applications. A new design of power management circuits is proposed in order to utilize the low ESR characteristics of super-capacitor and the low leakage current characteristics of the TFB in the hybrid energy storage. The average power loss due to leakage current is measured at 38μW in the proposed system. When Compared to the super-capacitor energy storage with the similar capacity, the proposed hybrid energy storage unit reduces the leakage power by approximately 45% whilst maintains a similar (<100 mΩ) ESR.

1. Introduction

In recent years, energy harvesting (EH) techniques have been frequently used for wireless sensor networks (WSN) applications in order to provide a long-term "self-powered" power supply. Within the energy harvesting system, energy storage unit (ESU) is a key component. ESU provides an energy "buffer" to temporarily store the harvested energy for WSN.

The characteristics of ESU have significant impact on the performance of the EH system. Two types of characteristics of ESU are considered in this work. The first type is the characteristics associated to system long-term lifetime, which includes energy density (and its ageing effects), operation lifetime, limit of rechargeable cycles. These parameters determine the "long-term operation lifetime" of ESU in terms of years. In addition to these parameters, the second type of characteristics determine the "efficiency" of ESU. Parameters such as leakage current and equivalent series resistance (ESR) lead to power losses when ESU is charged/discharged. These parameters contribute to the "short-term lifetime" of EH powered WSN, i.e. how long the EH powered WSN will remain active when only utilizing the stored ESU energy.

Super-capacitor and thin film solid state battery (TFB) have been proposed for the applications of energy harvesting [1, 2]. This is mainly due to their "long-term lifetime" characteristics. Super-capacitors have demonstrated lifetime more than 20 years and over one million rechargeable cycles [3]. TFB also have lifetime more than 10 years and over 10 thousands rechargeable cycles [4]. From this perspective, super-capacitor and TFB are more suitable for

EH application than state of the art rechargeable battery, which has <1000 charge cycles and less than 10 years lifetime [3].

However, from the aspect of ESU efficiency, issues exist in both super-capacitor and TFB.

1) Super-capacitor with 1-10F capacitance has a typical leakage current of 0.01-0.1 mA. For example, for Maxwell PC10 2F 5.0V super-capacitor, the average leakage current is measured at 40μA [5] in the first 12 hours of discharge. For applications charge/discharge with 0.1-10A current, e.g. camera flash light, the μA level leakage current is negligible [6]. However, in the application of EH powered WSN, the charge/discharge current is several orders of magnitude lower at 0.1mA level. Table 1. shows the power consumption of a temperature/light monitoring WSN system. In this case of low power WSN module, the leakage current of super-capacitor, 40μA, is more than 2 times higher than WSN module average current consumption, 16μA.

Table 1. The power Consumption of a Tyndall mote at 3.3V (Sleep mode is 300 seconds, i.e. 5 minute measurement interval)

Mode	Symbol.	Power (mW)	Current (mA)	Time (mSec)	Energy (mJ)
Active Mode	P_{Act}	57.1	17.1	87	4.97
Sleep Mode	P_{slp}	0.033	0.01	300,000	9.9
Average	P_{avg}	0.050	0.016	300,087	14.87

2) TFB has a low leakage current (less than 1μA). However, the ESR of the TFB is 50-75Ω in Infinite Power Solutions MEC series TFB [7]. When the active mode current of 17.1mA is discharged from TFB, 14.6mW of conduction loss ($I^2 \times R$, assuming R= 50Ω) can be attributed to the internal resistance. In this low duty cycle WSN example, 5μW power loss can be attributed to ESR. For WSN mote with higher active mode power consumption and longer active mode time, power loss due to TFB ESR is more severe.

Both the super-capacitor leakage power loss, 132μW (40μA $\times$3.3V), and the TFB ESR conduction loss, 5μW (1.6μA$\times$3.3V) contribute to the total power consumption of the WSN system. When the ESU power losses 137μW are compared with the WSN average power consumption, 50μW, the power losses of ESU are higher than the WSN power consumption.

In this work, super-capacitor and TFB hybrid energy storage is proposed with charge/discharge control circuits to reduce the power losses due to high leakage in super-capacitor and high ESR in TFB. The concepts of the hybrid ESU are: the optimized ESU with control circuits operate super-capacitor as the main storage unit and the TFB as the secondary storage unit. The super-capacitor is continuously connected to the load whilst its voltage is limited to within pre-set thresholds. Thin film battery is charged when the super-capacitor voltage excesses the voltage threshold. During high power active mode, the current consumption is mainly dissipated from super-capacitor instead of TFB.

2. Super-capacitor and Thin Film Battery Characterizations

Super-capacitor equivalent circuit model [8] has been used to simulate the leakage current of super-capacitor. In this model shown in Figure 1(a), three RC circuits are used to simulate a super-capacitor. The first RC circuit R_1, C_1 and C_V models immediate behaviour. The second RC circuit R_2, C_2 simulates the delayed behaviour with time constants on the level of 10s of minutes. The leakage current is simulated by the variable resistor R_3.

When the DC source is disconnected, charge re-distribution occurs between the first and second RC circuits. Self discharge occurs on variable leakage resistor R_3. The leakage current is determined by the terminal voltage V_O and the value of R_3. When the terminal voltage of super-capacitor is close to its voltage rating, the leakage current is significant higher than the

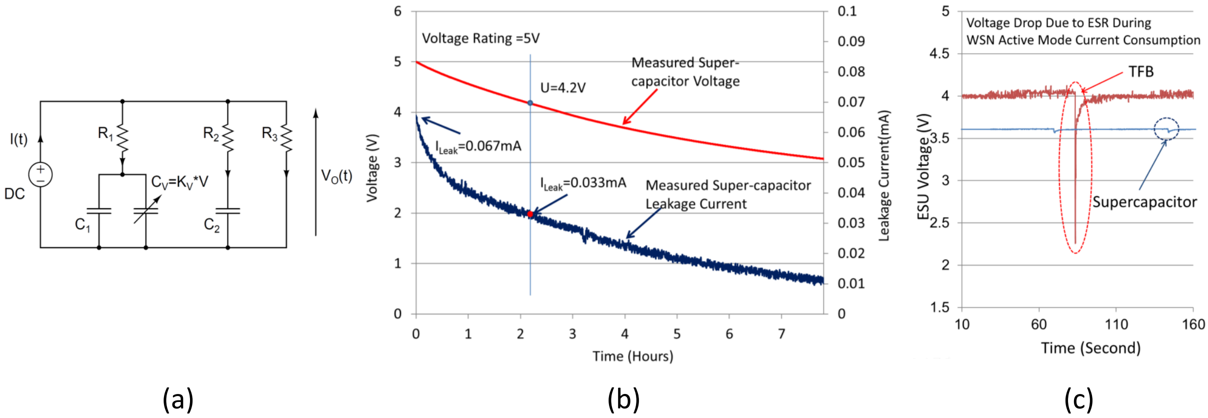

Figure 1. (a) Super-capacitor Equivalent Circuit with Leakage Resistor (b) Maxwell Super-capacitor PC10 self-discharge characterizations (c) Voltage Drop Due to ESR of Thin Film Battery

leakage current when the terminal voltage is 85% of voltage rating. Self discharge experiments have been conducted to investigate the leakage currents of the aforementioned Maxwell PC10 super-capacitor.

Figure 1 (b) shows the results of self discharge experiments conducted on Maxwell PC10 super-capacitor. The leakage current is 0.033mA when the super-capacitor voltage is 4.2V (85% of voltage rating). The leakage current at 100% of the voltage rating 5V is 0.067mA. Thus, by reducing the voltage of the super-capacitor by 15%, the leakage current can be reduced by 50%.

In order to calculate the power loss due to ESR in super-capacitor and TFB, both ESUs are tested with Tyndall WSN module. Both ESUs are connected to Texas Instruments TPS63036 buck-boost switching regulator to generate regulated 3.3V for the WSN module. The test results are shown in Figure 1 (c). Based on the measured voltage drop of 1.75V due to ESR of TFB and the peak current of WSN mote 25.1mA, the ESR of TFB is 70Ω. The power loss due to the ESR of TFB is calculated at 9.3μW,. The super-capacitor ESR is measured at 1.5Ω. The power loss due to ESR of super-capacitor is only 0.18μW, which is 47 times lower than the power loss due to TFB ESR and less than 1% of the WSN power consumption.

Based on these characteristics, if the super-capacitor is connected to the load as the main ESU and supply the active mode current, the power loss due to ESR can be reduced. In practice, this can be achieved by connecting super-capacitor and TFB in parallel. However, the “hard-wired” parallel connection is not suitable, since the TFB has operation voltage range of 3.8V to 4.2V whilst the super-capacitor operation voltage range is 0V to 5V. Over-voltage and under-voltage protection circuits must be included to limit TFB to its operation voltage range.

3. Hybrid Energy Storage Unit and Power Management Circuits

Based on the characterizations of the TFB and super-capacitor ESUs, the hybrid energy storage unit should be designed to 1) reduce the average super-capacitor voltage; 2) discharge the WSN active mode current from super-capacitor; 3) perform over-voltage and under-voltage protection for TFB.

The schematics designed for the hybrid ESU are shown in Figure 2. The super-capacitor is directly connected to the output voltage regulator. Three switches are used to connect/disconnect the TFB with the super-capacitor. These three switches are controlled by three out of four channels of a voltage comparator Maxim Max934. Max934 includes an internal reference which is set to 1.25V in this work. The total current consumption of the control logic circuits is less than 2μA.

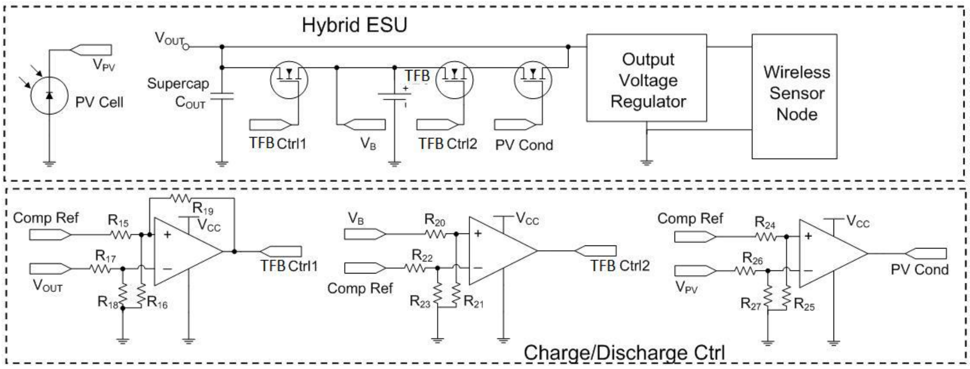

Figure 2. Schematics of hybrid ESU power management circuits

The control circuit limits the hybrid ESU voltage to a pre-set threshold of 4.2V in order to reduce the leakage current. Once the super-capacitor voltage is above the 4.2V threshold, "TFB Ctrl1" switch is turned on, the energy harvester will charge the additional energy into TFB for its low leakage current characteristics.

During the discharging, however, the TFB is always discharged first, and is connected with super-capacitor in parallel in order to minimize the ESR. This discharge only occurs when there is no input solar power. This is facilitated by "PV Cond" switch. The solar cell voltage, V_{PV} is compared with reference voltage. "PV Cond" switch is only switched on when V_{PV} is less than 1V, which indicates low light intensity condition. "TFB Ctrl2" switch is used to perform under-voltage protection of TFB. Once the TFB voltage V_B is lower than 3.8V cut-off voltage, the discharge of TFB is switched off by "TFB Ctrl2" switch.

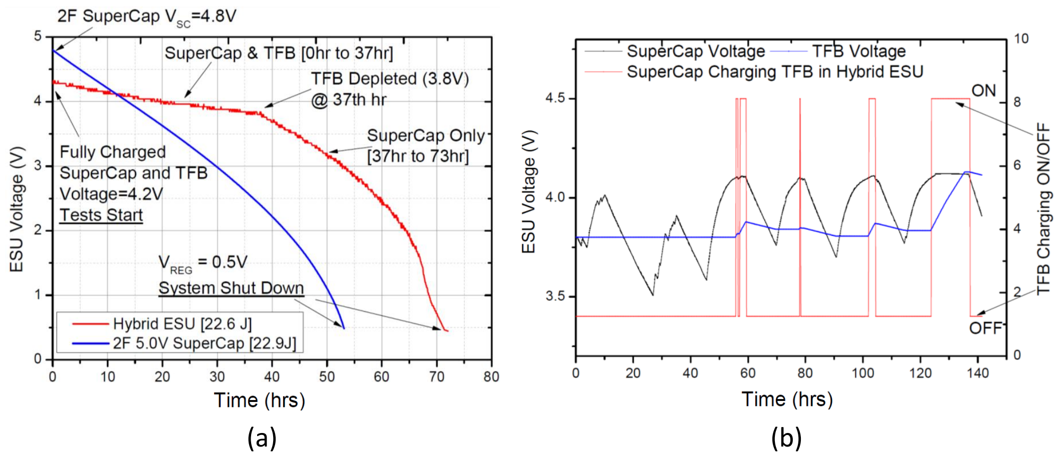

Figure 3. (a) Hybrid energy storage unit discharge experiment with a Tyndall WSN mote. (b) 1 week long charge/discharge test with 0.5mW PV cell and a Tyndall WSN mote. Black: super-capacitor Voltage; Blue: TFB Voltage; Red: super-capacitor charges TFB function ON/OFF

The prototype circuits are connected to a Maxwell 0.47F 5.0V super-capacitor and an Infinite Power Solutions TFB with 1mAh 4.2V capacity. The hybrid ESU prototype has been tested in two experiments shown in Figure 3. The first experiment shown in Figure 3(a) demonstrates the discharge process of the hybrid ESU when the load is the aforementioned Tyndall WSN module. The total operation time is 73 hours. The fully charged hybrid ESU has 22.6J capacity in total, with the super-capacitor and TFB (at 4.2V) store 8.2J and 14.4J energy, respectively. The power consumption of Tyndall WSN module and power loss in the proposed ESU is calculated at 0.088mW based on the 73 hours operation time. The average power consumption of Tyndall WSN module is 0.05mW when it operates with 5 minutes measurement interval (shown in Table 1). Thus, average power loss due to ESU is calculated at 38μW.

A Maxwell 2F 5.0V super-capacitor stores 22.9J energy when it is charged to 4.8V, which is 97% of its voltage rating. Its stored energy is 1.3% more than the 22.6J energy capacity of the proposed hybrid energy storage. The discharge process of this super-capacitor is also shown in Figure 3(a). The operation lifetime is 52 hours. The average leakage power of the stand-alone super-capacitor ESU is calculated at 69μW. The proposed hybrid ESU extends the operation lifetime from 52 hours to 73 hours in this experiment.

One week long charge/discharge experiments have been conducted to test the functionality of the control circuits. The results are shown in Figure 3(b). The super-capacitor charges the TFB at Day 3/4/5 of the experiment when it is charged to the pre-set 4.2V threshold and fully charges the TFB in Day 6. TFB is partially discharged during the night of Day 3/4/5 where no solar energy is available and the TFB voltage is higher than the 3.8V under-voltage protection threshold.

4. Conclusions

This paper presents a super-capacitor and thin film battery hybrid energy storage solution. The characterization of super-capacitor shows that the leakage current can be reduced by more than 50% by decreasing the operation voltage from 100% to 85% of its voltage rating. By connecting the thin film battery and super-capacitor in parallel in order to reduce the equivalent series resistance of the thin film battery, the power loss due to ESR can be reduced from 9.3μW to 0.2μW. By utilizing these two characteristics with the charge/discharge control circuits proposed in this work, the average power loss of ESU is only 38μW. When compared to the stand-alone super-capacitor ESU with same capacity, the power loss is 45% lower. The 22.6J capacity of the hybrid ESU powers a wireless sensor module to perform light and temperature monitoring every 5 minute for 73 hours.

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