Estimation of the Dynamic Leakage Current of a Supercapacitor in Energy Harvesting Powered Autonomous Wireless Sensor Nodes

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***Abstract*— The supercapacitor is a candidate energy storage component for energy harvesting powered autonomous wireless sensor node aiming to achieve battery replacement-free, "fit and forget" sensor node in low-power IoT applications. The leakage current of the supercapacitor provided by the manufacturer is tested long after post-charge, raising a concern relating to the uncertainty of the dynamic leakage current in the IoT applications where the supercapacitor frequently charges and discharges. This paper investigates the charge redistribution process which causes an equivalent capacitance change of the supercapacitor in a full IoT measurement period, and then proposes an experiment design to measure the dynamic leakage current of a supercapacitor for an IoT application. The results showed that the charge redistribution process is completed long before the end of the sleep period due to the low ratio of the amount of discharge in an active period to the total amount of charge the supercapacitor holds. It also showed that the average dynamic leakage current in an entire measurement period corresponds to the value provided by the manufacturer, indicating that leakage current is not an issue when supercapacitors is used for low-power IoT applications.**

Keywords—supercapacitor; leakage current; charge redistribution; IoT

I. Introduction

The Internet of Things (IoT) is believed to be the next generation of the internet with an estimated trillions of sensor nodes [1], calling for "fit and forget" autonomous wireless sensor node to lower the maintenance costs. In building automation, using in-door photovoltaic (PV) energy harvester, together with energy storage supercapacitor provides the powering solution in which the required energy for powering a short measurement period can be accumulated from the harvested weak energy in the relatively long sensor sleep period.

Frequently a supercapacitor's leakage current is specified by the manufacturer as a value measured long after post-charge (such as 72 hours post-charge [2]), while in IoT applications the supercapacitor continuously keeps charging in sleep mode and discharging in active mode. The measurement period of such a charge/discharge process is most unlikely longer than 72 hours, therefore the actual leakage current of supercapacitor in IoT applications is an unknown technical parameter when a supercapacitor is used as the energy storage component for energy harvesting.

The characteristics of the supercapacitor have been investigated in different circuit models [2-7]. Several of them [2-4] have already addressed the non-linearity caused by the charge redistribution. However, the model parameters are not easy to obtain for a complicated model while less parameter models have been criticized for being over simplified. Furthermore, researchers [3, 8] show that charge redistribution process is not only dependent on the supercapacitor model but also on a set of other parameters such as charge voltage and charge duration/charge current, so in practice the model based leakage estimation is hard to use.

This paper investigates the dynamic leakage current of the supercapacitor in IoT applications. Based on the IoT power pattern, a leakage current measurement method for IoT applications is proposed, which can directly calculate the dynamic leakage current using the measured terminal voltage of supercapacitor in an entire measurement period to bypass the complicated charge redistribution process.

II. Charge Redistribution in Supercap

The supercapacitor is a capacitor with electrolyte, which creates internal chemical process (diffusion or mass transfer) for charge redistribution after charge/discharge. The time constant of the diffusion process has been reported in days for huge capacitances (such as thousands Farad), so the leakage current of a supercapacitor has been specified after the completion of the diffusion process (several days post-charge). The supercapacitor has been modelled as RC circuits to investigate its characteristics such as terminal voltage, charge redistribution and energy stored inside the supercapacitor. A typical supercapacitor model is composed of a leakage path of R_{leak} and a number of parallel *RC* branches as shown in Fig. 1. The time constant to fully complete the charge redistribution process in Fig. 1 can be expressed as,

$$\tau = \sum_{i=0}^{n}(C_i \times \sum_{j=0}^{i} R_j) = R_0C_0 + (R_0 + R_1)C_1 + \cdots + (R_0 + R_1 + \cdots + R_n)C_n \quad (1)$$

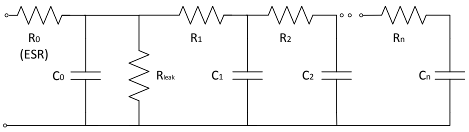

Fig.1 A typical equivalent circuit model of the supercapacitor

In practice, it is difficult to determine the parameters of model order (n) and then the 2n parameters for R and C.

After the charge redistribution process is completed, the currents flow through the resistors should be zero therefore all capacitors are in parallel virtually. The equivalent capacitance change in a charge redistribution process can be expressed as,

$$C \cong C_0 + \sum_{i=1}^{n} \Delta C_i \times U(t - \sum_{k=1}^{i} R_k \Delta C_k) \quad (2)$$

where U(t) is the function of

$$U(t) = \begin{cases} 0 & when\ t < 0 \\ 1 & when\ t \geq 0 \end{cases} \quad (3)$$

and the C is the nominated capacitance of a supercapacitor. Formula (2) shows that the capacitance of a post-charge supercapacitor increases with time to reach its nominated value at the end of the charge redistribution process.

The equivalent capacitance shown in (2) provides an alternative way to understand the large voltage drop at the beginning of post-charge: the equivalent capacitance is boosted and as a result, an exponential voltage drop can be observed at the beginning of the post-charge terminal voltage curve. The terminal voltage of the supercapacitor is finally stable after the completion of the charge redistribution process. For example, the stable terminal voltage V_t in the simplest supercapacitor model (when n=1 in Fig. 1) can be expressed as $V_t = V_0 C_1/(C_1 + C_0)$ where V_0 is the terminal voltage of the supercapacitor at the beginning of post-charge.

The power loss of the supercapacitor for energy harvesting wireless sensor nodes has been simulated [8, 9]. However the leakage current could not be precisely estimated by supercapacitor models without extra charge history information due to the capacitance change caused by the charge redistribution process. A generic method is required to directly measure the leakage current of the supercapacitor in low-power IoT applications where the actual leakage current is an unknown parameter.

III. METHOD TO MEASURE DYNAMIC LEAKAGE CURRENT IN IOT APPLICATIONS

A typical power requirement for a low-power wireless sensor node in an IoT application is shown in Fig.2. The short-term active mode requires a current pulse of 20 mA (low-power sensors consume sub-mW power, and the typical current required for a short-range radio is about 20 mA although wireless communication can consume up to 20 dBm = 100 mW for industrial scientific and medical (ISM) band radio). The long-term sleep mode consumes μA level current to keep the microcontroller of the sensor node continuously working. The weak current generated by the energy harvester is also shown in Fig. 2 as the dashed line. The limited current form energy harvester is due to reasonable size and the low power density of the energy harvester (eg. 10~20μW/cm^2 for photovoltaics (PV) energy harvesting, 0. 1μW/cm^2 for GSM and 0.001μW /cm^2 for WiFi). In an energy harvesting powered wireless sensor node, the sleep period must be much longer than the active period, since it takes time to accumulate enough energy in sleep mode for regenerating a high-energy current pulse in active mode.

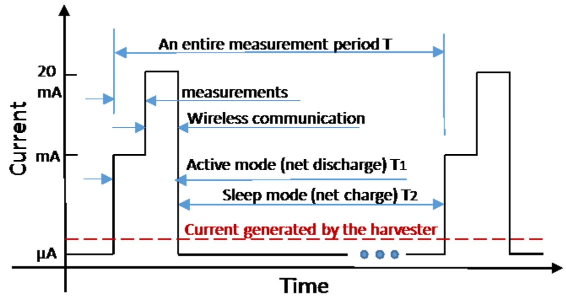

Fig.2 Power requirements of a wireless sensor node. Due to the weak energy harvested, T_2 >>T_1 since it requires $I_{harvester}$×T > I_{used} ×T_1 (T = T_1+T_2)

When a smaller than a credit card size PV panel is employed as the in-door energy harvester, it can generate a relatively small current such as 47 μA at 200 lux (ordinary room illumination condition). If the PV panel is directly connected to the energy storage supercapacitor, a simplified schematic of the wireless sensor node is shown in Fig.3, where R_1 and R_2 are the equivalent resistive loads of the wireless sensor node in active and passive periods of T_1 and T_2.

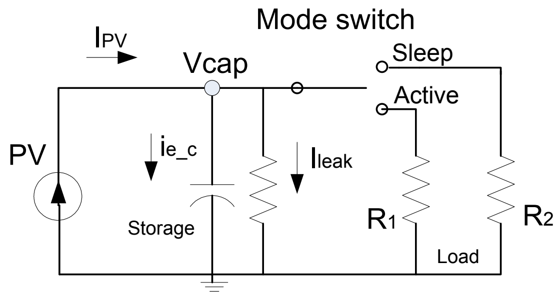

Fig.3 Equivalent circuit diagram of a wireless sensor node powered by a PV with an energy storage supercapacitor

The PV panel in Fig.3 is expressed as a current source, since the I-V relationship of a PV cell is

$$I_{cell} = I_{sc} - I_0 \exp\left(\frac{V_{cell} + R_s I_{cell}}{\frac{KT}{q}} - 1\right) - \frac{V_{cell} + R_s I_{cell}}{R_p} \quad (4)$$

where I_{sc} represents the photon current which is proportional to intensity of incoming light (illumination) and the area of the cell, and I_0 presents the leakage of the electrons and carrier recombination. R_p denotes the shunt resistance representing the loss incurred by conductors, and the R_s represents the loss of non-conductors. At a given illumination condition the output current of the PV is a constant.

The power management strategy for indoor PV energy harvesting is adopted as to count the net charge of the supercapacitor in the term of

$$I_{pv}\times T - I_{leak}\times T - (V_{cap}/R_1)\times T_1 - (V_{cap}/R_2)\times T_2 \quad (5)$$

If the net charge is not negative then the terminal voltage of the supercapacitor will not drop, which guarantees the continuously powering the sensor node.

It seems that the leakage current shown in Fig.3 can be obtained by measuring the terminal voltage of the supercapacitor in an entire measurement period and then apply the formula:

$$C\Delta V_{cap} = I_{pv}\times T - I_{leak}\times T - \frac{\int_{t_1}^{t_1+T_1} v_{cap}dt}{R_1} - \frac{\int_{t_1+T_1}^{t_1+T_1+T_2} v_{cap}dt}{R_2} \quad (6)$$

where t_1 is the start point in a measurement period and ΔV_{cap} is the voltage difference of the supercapacitor after a full measurement period.

The concern of using formula (6) is that the formula employs the nominated capacitance as shown in (2), which happens only when charge redistribution process is entirely completed. Even with considering the fact that time of sleep mode is much longer than that of the active mode, evidence is still lacking that the charge redistribution can be completed by the end of sleep mode.

The charge redistribution time for the simplified model shown in Fig. 4 can be calculated as,

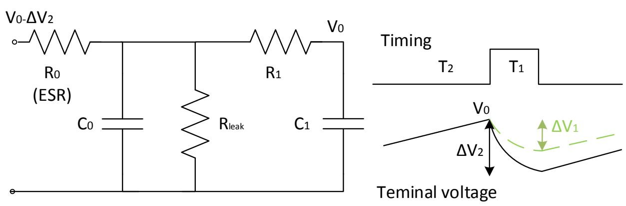

Fig.4 Charge redistribution caused terminal voltage change

$$\begin{cases} Q = I_{discharge}T_1 = (C_0 + C_1)\Delta V_1 \\ C_0\Delta V_2 = Q \\ V_0 - \Delta V_1 = V_0 \exp\left(-\frac{t}{R_1 C_0}\right) \end{cases} \quad (7)$$

where Q is the total discharge in active period, V_0 is the terminal voltage before discharge (at the end of T_2), ΔV_1 is the idea voltage drop when the supercapacitor is working at the full capacitance and ΔV_2 is the actual terminal voltage drop in the worst case that only C_0 is involved in the discharge process. Therefore the charge redistribution time can be estimated by discharge C_1 from V_0 to V_0-ΔV_1 through the path R_1 as,

$$t < R_1 C_0[ln(V_0) - ln(V_0 - I_{discharge}T_1/(C_0 + C_1))] \quad (8)$$

Formula (8) demonstrated that the charge redistribution process not only depends on model parameters of R_1, C_0, C_1 but also on active mode discharge (discharge current, discharge time) and the starting discharge voltage. Therefore even with the supercapacitor model parameters obtained by applying extra signals from outside, such as a voltage pulse [6] or a current pulse [7], how to judge whether the charge redistribution process has completed is still an issue. Without this condition, formula (6) does not work due to the inconsistent capacitance shown in formula (2).

On the other hand, if thinking about the linearity of the terminal voltage of the supercapacitor in a full measurement process, it is possible to judge whether the charge redistribution process is complete when the linearity of the terminal voltage is checked by considering

$$C = dQ/dV_{cap} = I_{char}\times(dt/dV_{cap}) = I_{char}/(dV_{cap}/dt) \quad (9)$$

where I_{char} is the constant charge current from the PV deducting the I_{leak}. This means that as long as the dV_{cap}/dt is a constant, the supercapacitor is in the steady state with the nominal capacitance (a completion of charge redistribution process). So the method proposed here is to measure the terminal voltage of the supercapacitor in a whole measurement period (active + sleep) with simulated IoT loads so that the total discharge by the load is a known value. Using the terminal voltage data as an indication of the completion of the charge redistribution process so that formula (6) can be used for dynamic leakage current calculation. In this way the complicated charge redistribution process can be bypassed. Since charge redistribution process does not lose any charge, the supercapacitor's charge information will be correctly presented in terminal voltage after the completion of the charge redistribution process.

IV. MEASUREMENT EXPERIMENTS

A. Experiment set-up

The leakage current test experiment has been set-up based on Fig. 3. A commercially available PV panel of AM-1815 from Sanyo is employed to supply 47.0 µA current at 200 lux. A power management chip of LTC4071 is employed to protect the supercapacitor from overcharge and over-discharge. The supercapacitor under test is a VinaTech 5.4V 0.5F. The resistor R_1 and R_2 are 200 Ω and 1 MΩ representing the sensor node in sleep mode (4.0µA current) and active mode (20 mA current) at 4.0V supply. The mode switch is controlled as 250 ms active in the 150 s full measurement period. The start-up terminal voltage of the supercapacitor is 3.7 V.

B. Results

The terminal voltage of the supercapacitor in four successive periods has been recorded. Fig. 5 shows the 500 ms data around active period. The bottom curve is for the first period. The terminal voltage goes higher after each period, indicating that the total charge in a whole measurement period is larger than the total discharge in the period. The active mode start from 150ms and end at 400 ms. The ~120 mV voltage jumps at the beginning and end of the active mode is caused by the 6Ω internal resistance of LTC4071.

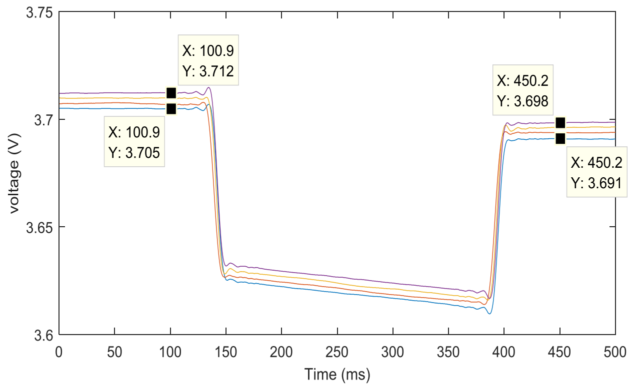

Fig.5 Recorded voltage of four successive periods around active period.

The linearity of terminal voltages from 0 to 100 ms has been checked. The terminal voltages of period 1 and period 4 at the end of T_2 (100 ms point in Fig. 5) have been marked, which shows a 7.0 mV voltage rise. After calculating the amount of discharge in the active and sleep periods, the dynamic leakage current of the supercapacitor has been calculated as 1.8 µA using formula (6). This leakage value is almost as low as the leakage current of 2.0 µA specified by the manufacture (tested after 72 hours of post-charge at the terminal voltage of 5.4V).

C. Discussion

Since the terminal voltage of the supercapacitor in the period of 0-100 ms (before the end of T_2) is linear, it is no problem to use entire capacitance value for formula (6). However, if using formula (6) in active period (150 to 400 ms shown in Fig. 5) as

$$I_{pre} = \frac{\int_{t_1}^{t_1+T_1} C\,dv_{cap}}{T_1} + I_{leak} + \frac{\int_{t_1}^{t_1+T_1} dv_{cap}}{R_1} \tag{10}$$

The calculated dynamic leakage current is 8.6 mA. This demonstrates that the terminal voltage in the active mode could not be directly used for leakage calculation, since the incomplete diffusion process affects the terminal voltage. If this voltage must be used then it is important to note that the capacitance of the supercapacitor in this period is not the same as the manufacturer's specified one.

From formula (8), the charge redistribution time can be expressed as

$$t < R_1 C_0 \ln\left(\frac{1}{1-\frac{\Delta V_1}{V_0}}\right) = R_1 C_0 \ln\left(\frac{1}{1-\frac{I_{discharge}T_1/(C_0+C_1)}{V_0}}\right)$$
$$= R_1 C_0 \ln\left(\frac{1}{1-\frac{Q_{discharge}/(C_0+C_1)}{Q_{total}/(C_0+C_1)}}\right) = R_1 C_0 \ln\left(\frac{1}{1-\frac{Q_{discharge}}{Q_{total}}}\right) \tag{11}$$

Note that the total discharge in this experiment is about 5mC which results in about 10 mV terminal voltage change for the 0.5F supercapacitor. Given that the start voltage V_0 is 3.70 V, the time constant for the charge redistribution in this case is 0.001 times R_1C_0. As a result, the terminal voltages of period 1 and period 4 at 450 ms point (soon after the end of T_1) shows a 7.0 mV voltage rise as well, suggesting a completed charge redistribution process. The explanation is that with the commonly used model parameters [6, 9] (roughly say that C_0/C_1 = 4:1) and the 5 mC discharge in active mode, the supercapacitor's terminal voltage change in the charge redistribution process is as small as 2.5 mV, corresponding to a short the charge redistribution process.

V. CONCLUSION

The dynamic leakage current of the supercapacitor in low-power IoT applications has been measured. It is based on the charge measurement of the supercapacitor with the assumption that the charge redistribution process after the discharge in active mode can be completed in the relatively long sleep mode. A leakage current test experiment simulating a supercapacitor in an IoT application demonstrated that the charge redistribution process completed shortly after active mode due to the very small ratio of the amount of discharge in active mode to the total charge the supercapacitor holds. The proposed method bypassed the complicated modelling and calculating of charge redistribution process, providing a practical leakage measurement method for supercapacitors in IoT applications. Measurement results show that the dynamic leakage current is as low as the manufacturer specified leakage current at 72 hours post charge, indicating that supercapacitors can be used in low-power IoT applications without a further leakage concern.

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