Design and Performance Analysis of Supercapacitor Charging Circuits for Wireless Sensor Nodes

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***Abstract*—We propose a charge pump type of supercapacitor-charging circuit for energy harvesting application to perform maximum power transfer tracking (MPTT). The charging circuit supplies a train of current pulses to charge an energy-storing supercapacitor array to a doubled voltage, converting input power obtained from ambient energy sources. The connection of multiple energy storage supercapacitor is reconfigurable by means of a simple switch array. The voltage doubler charge pump and the smart switch array not only enable the sensor nodes to operate under low ambient power conditions but also improve the charging speed. The operation of the supercapacitor charging strategy was validated by simulation.**

***Index Terms*—Energy harvesting, supercapacitor charging, maximum power transfer tracking, charge pump**

I. Introduction

ENERGY storage element (ESE) are essential elements in energy harvesting systems (EHS) for many wireless sensor nodes that must continue to operate even if there is not sufficient power from the environment. To date, batteries are the primary type of ESE for wireless sensor nodes and many other embedded systems due to their cost, energy density, and maturity of technology. However, they can suffer from non-ideal effects such as the memory effect and the limited number of recharge cycles. For solar-powered sensor nodes, the ESE of an energy harvester experiences deep discharge cycles every night, thereby ensuring that such limitations of batteries will cause recurring maintenance cost. To compensate or overcome these disadvantages of rechargeable batteries, in recent years, hybrid power sources [1], [2] or supercapacitor-only supplies [3]–[5] have emerged in a range of applications.

Supercapacitors, also known as ultracapacitors or electrochemical double layer capacitors (EDLCs), have extremely long life cycles, and therefore they have been identified as a promising type of ESE for sensor nodes. In particular, supercapacitors and photovoltaic (PV) modules make an excellent combination for energy harvesters. This has motivated researchers to design efficient charging circuits for supercapacitors in their sensing systems.

The main issues with EHSs are constraints on the form factor, harvesting efficiency, autonomy of harvesting control, scalability to multiple reservoirs, and cold booting control. To solve these issues, it is critical to devise (1) charging circuits to maximize harvesting efficiency and (2) the circuits to automatically find the maximum power point (MPP). They can lead to several benefits such as: i) cost-effective system; ii) small form factor of harvesting system; iii) the long operating lifetime.

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A. Problem Statement

1) MPPT vs. MPTT: High-efficiency conversion systems usually exploit maximum power point Tracking (MPPT) techniques to continuously deliver the highest possible power to the load [6]. However, MPPT techniques pose challenges to small systems such as wireless sensors. First, it is hard to build one such mechanism that also performs MPPT on other ambient power sources due to their wide dynamic range. The harvesting efficiency can easily drop by one to two orders of magnitude if MPPT cannot cover this wide dynamic range. Second, conventional MPPT simply finds the MPP of ambient sources regardless of charging circuits efficiency [7], but it might not be the actual MPP at the system level. Because charging circuit efficiency is a function of the load, maximum power *transfer* tracking (MPTT) was proposed to consider the maximum efficiency tracking of the charging circuits. To realize MPTT, we propose a novel charging circuit using a charge pump to charge supercapacitors. Since frequency sweeping range of a charge pump is directly related to the wide dynamic range of various ambient power sources, we utilize a direct digital synthesizer (DDS) to cover the wide dynamic range of the charging circuit.

2) Buck-type charging circuits: Previous buck-type charging circuits [3], [5], [8] require the use of an inductor as a low pass filter (LPF), which increases the size of the harvesters, as the inductor tends to be bulky. In this work, we overcome this design issue by using a charge pump, which does not require any additional inductors, thereby enabling us to better meet the size constraint.

3) Charging nearly fully depleted supercapacitors: Even if supercapacitors are the most promising ESE for sensor nodes, charging supercapacitors that are nearly fully depleted can cause other problems: inrush current and cold booting. *Inrush current* is an effective short circuit when the load is a nearly empty supercapacitor. *Cold booting* is the futile cycles of repeated booting and exhaustion due to insufficient stored energy. The proposed charging circuit can control charging speed by adjusting the charge pump switching frequency to reduce inrush current. The cold booting problem is addressed by a combination of a sensor and a smart switch array that shortens the supercapacitor charging time.

B. Contributions

The contributions of this paper are as follows:

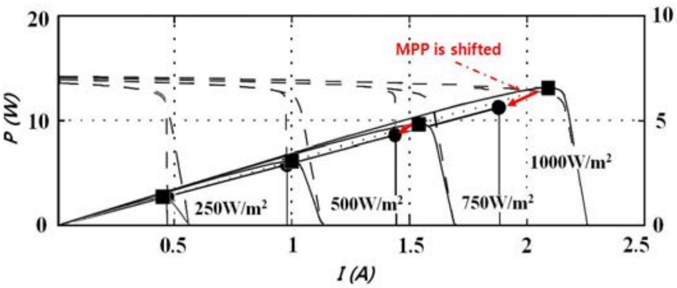

Fig. 1. MPP_{scap} vs. MPP_{solar}, when $P_{scap} = \eta \cdot P_{abmi}$. [7]

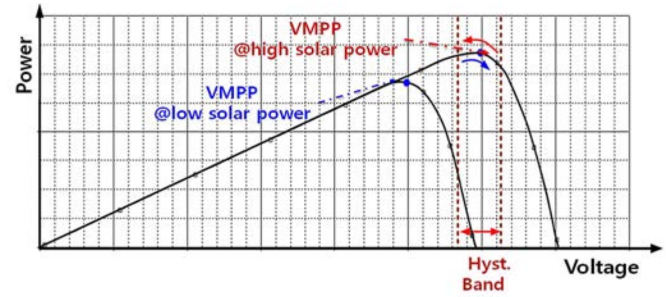

Fig. 2. P-V Characteristics and Hysteresis Window of the MPP

- We develop a boost-up charge pump supercapacitors charging circuit to enables systems such as wireless sensor nodes to work under low ambient power conditions.
- A maximum power *transfer* tracking strategy with a wide dynamic range is realized by tuning the charge pump switching frequency.
- A smart reconfigurable switch array is proposed for shorter charging times as well as energy balancing for the reservoirs supercapacitors array (RSA).

II. Background and Related work

A. Backgrounds

1) The impact of charging-circuit efficiency on MPP: Because the charging circuit efficiency η is varying depending on output current I_{out}, conventional MPPT techniques cannot guarantee that the maximum P_{ambi} is equal to the maximum P_{scap}. That is, even if the conventional MPPT achieves the MPP from the ambient power sources, it never goes to the supercapacitor without considering the charging circuit's efficiency for the EHS.

Fig. 1 shows that MPP_{solar} marked by squares is shifted to MPP_{scap} as indicated by circles after passing through the charging circuit of the harvesting system. The amount of shift is linearly proportional to the output current I_{out}. For instance, at 1000 W/m^2, we can see a significant drift from MPP_{solar} to MPP_{scap}. Considering the variations in efficiency of charging circuit, the MPPT circuitry should be placed at the right before supercapacitors to implement a more accurate MPP tracker.

2) MPP Trackers: Through above MPPT techniques, once a MPP is determined, we need to fix an operating point of a charging circuit to the MPP. LTC1440, ultra-low power comparator made by Linear Technology, is a popular component for MPP tracker [5], [8], [9]. With a programmable hysteresis function, the LTC1440 can adjust its lower and upper bounds of the hysteresis band as shown in Fig. 2. In this way, the actual operating point of the MPP tracker oscillates around the MPP, rather than being a fixed point. By tuning to a low hysteresis band, this can lead to higher efficiency of a power converter.

Although the narrow hysteresis band makes the tracking operation more accurate, it might not be able to match all ambient power conditions, making the MPP tracker operate at a non-optimal power point. Taking PV cells as an example, if the solar irradiation intensity is low in the early morning, the MPP tracker with a narrow tuning hysteresis band works beyond the optimal power point as shown in Fig. 2. Therefore, an MPP tracker should be capable of covering a wide dynamic range.

B. Related Work

1) COTS DC-DC converter: After PV arrays convert solar power into electrical form, commercial off-the-shelf (COTS) DC-DC converters are used in several designs [2], [9], [10] to extract the maximum power from the PV arrays under strong sunlight. By controlling the on/off switching duty cycle of the converter, the converter matches the impedance between ambient energy sources and ESE. That is, the duty cycle of the DC-DC converter is varied until the PV cells operation point reaches the MPP. Since the converter's output voltage is determined by both the converter's input voltage and the switching duty cycle, it would vary greatly. Thus, ESEs are required to supply stable power to a load. If the target system requires a different supply voltage from the ESE's voltage, then a second DC-DC converter such as a buck-boost converter is needed to generate a stable supply from the ESE.

However, COTS DC-DC converters require additional electrical components such as power transistors and inductors, which will increase the volume and the cost of the EHS. Besides, the power overhead of two COTS DC-DC converters may increase the system total power loss. Furthermore, when a supercapacitor is near depletion, it appears as a short circuit, or infinite load. In fact, EHSs that rely on feedback converters to charge supercapacitors (e.g., [9]) will suffer from this problem: the apparent infinite load can cause the charging circuit to reduce the current and charge the supercapacitor very slowly when it starts from empty.

2) Custom-designed Converters: A pulse frequency modulation (PFM) converter was proposed to address the problem with COTS feedback converters. The PFM converter has the advantages of both the switching capacitor regulator and the buck-down converter to prevent shorting the input and output. As a result, it can charge a supercapacitor efficiently from a high impedance power source [11]. However, a PFM converter perturbs the power supply path during MPP tracking using open circuit voltage, short circuit current, and I-V curve tracing. That is, the power supply will stop temporarily during perturbation. One alternative that solves this problem is to use a pilot cell, which is a miniature solar cell that outputs its harvested power [2]. Unfortunately, the MPPT circuitry using the above two types converters was implemented in front of the

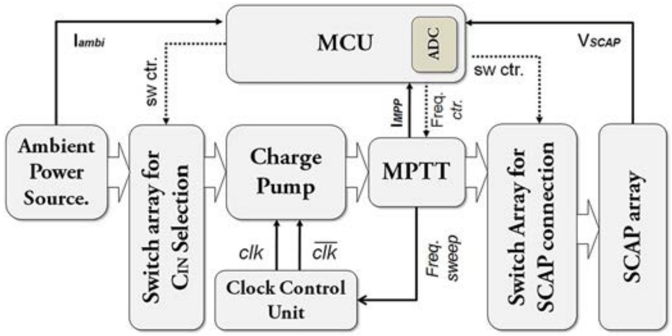

Fig. 3. System block diagram.

converters, which do not take the buck converter's efficiency into account. Hence, this would be not real MPP of PV arrays as mentioned in Section II-A.

3) Charging Pump Converter: Two ICs developed at Linear Technology, LTC3225 [12] and LTC4425 [13], inspired the idea of inductor-less converters as presented in Section II-B2. These ICs implement similar charging strategies, but the latter has additional functions such as current limiter using an ideal diode and current monitoring of V_{in} to V_{out}. Both focus on shrinking the solution size by employing a charging pump scheme while improving the efficiency over previous charging methods. Despite many advantages of two ICs, the ICs do not integrate the MPPT circuitry, which is absolutely necessary function, especially, micro-systems such as wireless sensor nodes or smart sensors.

Clearly, a more effective method of charging supercapacitors exists. This paper explores the frequency sweeping control methods for maximum power *transfer* tracking (MPTT) with variations in efficiency of the charging circuit, the charge pump scheme for a small form factor as well as fast charging, and the wide dynamic range of charging circuits under various ambient power sources.

III. Harvester System Design

Nowadays, charging circuits (e.g., a power converter) using a charge pump have gained popularity in wireless sensor systems for their smaller form factors, simpler structures, and faster charging rate [14]–[16]. According to Sokal [16], the fastest and most efficient method to charge a capacitor is to use the maximum peak switch current. Therefore, the charge pump is a good way to charge supercapacitors. The system block diagram with the proposed MPTT is shown in Fig. 3. There are four primary tasks in our proposed energy harvesting method: 1) sensing the current from ambient power source(s) and selecting suitable input capacitance C_{in}, 2) sweeping the switching frequency and tracking I_{MPP} using the *I-F curve*, 3) feeding a microcontroller unit (MCU) the *maximum transfer current* point (MTCP) and reconfiguring the smart switch array to optimize the input capacitors or connect the reservoir supercapacitors in series or as single cells, and 4) charging the selected supercapacitor with I_{MPP}.

The proposed charging circuits for EHS have a simple structure, as they merely require two extra capacitors, with no need for any additional inductors. Moreover, the charging rate can

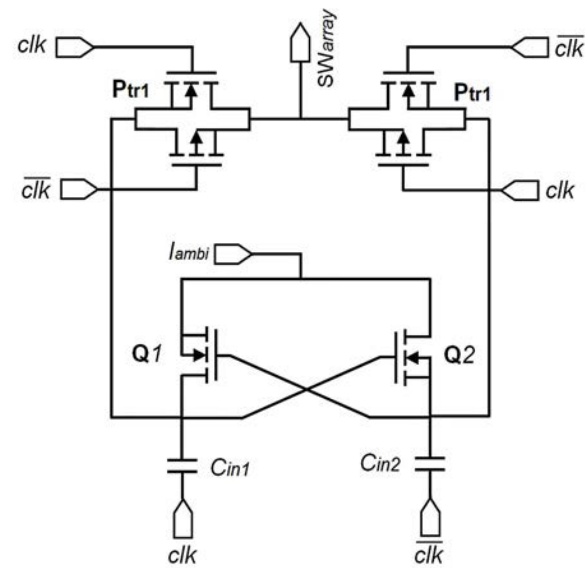

Fig. 4. Charge pump cell.

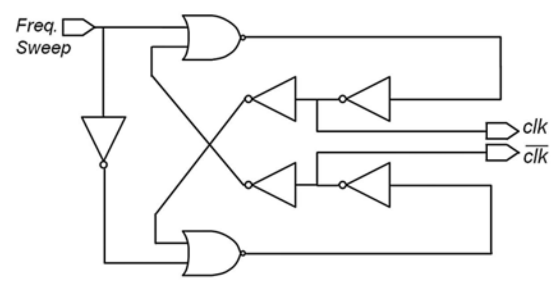

Fig. 5. Non-overlapping Clock controller.

be controlled by the charge pump through the current sensor feedback signal, thereby starting with a "soft" charging rate and reducing the short circuits of empty state supercapacitors at the same time.

A. Charge Pump

A charge pump converts an input voltage to one higher than the supply voltage. Fig. 4 shows how this is possible using the voltage doubler charge pump cell [17]. NMOS transistors pass a strong '0' but a weak '1' (threshold voltage drop, $High = V_{DD} - V_{tn}$) while PMOS transistors pass a strong '1' but a weak '0' (threshold voltage drop, $Low = V_{tp}$). Since it is important to reduce additional voltage drop in the application fields of low power consumption, the switches $Q1$ and $Q2$ are implemented by a pair of complementary MOS transistors in order to avoid additional voltage drop due to V_{th}.

Signals clk and $\overline{clk}$ are a non-overlapping clock pair with two different phases. During clock phase clk, $Q1$ closes to connect the I_{ambi} to the top plate of C_{in1} and the bottom plate of C_{in1} is connected to 0V to charge C_{in1}; at the same time, $Q2$ opens to disconnect the I_{ambi} from the top plate of C_{in2} and the bottom plate of C_{in2} is connected to V_{ambi}. This way, the top plate of C_{in2} is boosted to $2 \times V_{ambi}$. During clock phase $\overline{clk}$, the operation of the charge pump works similarly in the converse way.

After a few clock cycles, the clock signals on the top plates of the capacitors will assume an amplitude of $2 \cdot V_{ambi}$. The switches P_{tr1} and P_{tr2} are timed, so that V_{out} at the SW_{array} sees this voltage. If $V_{ambi} = V_{DD}$ then

$$V_{SWarray} = 2 \cdot V_{DD} \tag{1}$$

The charge pump requires non-overlapping and two-phase clock generator for high performance operation that is shown in Fig. 5. The non-overlapping clock can be generated using [18].

B. Frequency Sweeper

A charge pump can be operated from tens of kilohertz up to tens of megahertz in order to achieve the highest efficiency for the system. However, virtually all commercially available charge pumps use only one fixed frequency optimized for their predetermined source power capacities. This frequency will work reasonably well with most stable power source such as battery and USB power source, etc. It is not optimized for the variable power source that depend on the environment, as is the case for most EHSs. Ideally, a charge pump adapts its frequency to the power capacity. For the best dynamic range, an oscillator for the charge pump should be able to generate frequencies from kilohertz to megahertz, but it is a very broad range. The maximum tuning range of commercially available oscillator has 100% tuning range from a given center frequency. So, it is quite difficult to fulfill with a single analog oscillator. Although it is possible to cover this wide frequency range using multiple analog oscillators, doing so will increase system complexity and induce higher overall power consumption. For this reason, a DDS can be the best candidate for the charge pump as a substitute for a conventional analog oscillator. A commercially available DDS chip, AD9834, can generate frequencies from 0 to around 40 MHz with power overhead of around 18 mW. The frequency from the DDS can be fully controlled by an MCU with a very high resolution of frequency steps and with very fast switching time of typically around 50 ns.

C. Smart Switch Array

Using a single large supercapacitor for ESE is simple but it could suffer from cold booting [8], also known as the zero-energy boot-strapping problem, and high unusable remaining energy. To address these problems with single supercapacitors, reservoir supercapacitors arrays (RSA) were proposed [8], [9]. In particular, in [8], a *bootstrap supercapacitor*, which has relatively smaller capacitance than the primary energy storage, was used to solve the cold booting problem. In addition, a main disadvantage of supercapacitors is the higher leakage rate than rechargeable batteries. However, in [8], [9], the RSA is charged sequentially, thereby reducing the energy storage efficiency, because the leakage rate of supercapacitors increases rapidly as they reach their rated capacitance [19].

The design objective of the smart switch array is to improve the charging rate of supercapacitors and reduce the leakage rate by energy balancing of supercapacitors. Also, during charging, the MCU monitors each supercapacitor voltage

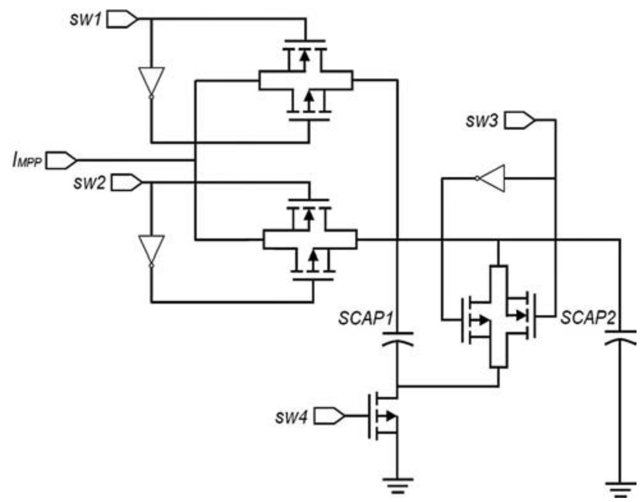

Fig. 6. Smart Switch Array for SCAP connection.

TABLE I
A SET OF SWITCH ARRAY CONNECTIONS

Connection Status	$SW1$	$SW2$	$SW3$	$SW4$
Charging S_{CAP1}	On	Off	Off	On
Charging S_{CAP2}	Off	On	Off	On
Charging in series	On	Off	On	Off
Charging in parallel	On	On	Off	On

and prevents its overvoltage by the reconfiguration of the switch array. Fig. 6 shows an example of the switch array operation to charge two supercapacitors ($SCAP1$ and $SCAP2$). When ambient power sources are enough, for example solar irradiation intensity is strong, the MCU decides to charge the supercapacitors in series by turning on $SW1$ and $SW3$. Two supercapacitors connected in series has twice the voltage but half the capacitance. As a result, the charging rate is increased even though the supercapacitors voltage is doubled, because the charging current is sufficient thanks to the voltage doubler charge pump. However, during charging supercapacitors in series, we need to monitor V_{SCAP1} and V_{SCAP2}. If either supercapacitor approaches the rated voltage, then the MCU controls the smart switch array to prevent overvoltage. In the case when the ambient power is scarce, the MCU monitors V_{SCAP1} and V_{SCAP2} and decides to charge the supercapacitor with a low voltage, since this has higher charging efficiency. This is because the leakage rate is exponentially proportional to the supercapacitor voltage [19].

The combinations of switching connection are shown in Table I. The smart switch array can easily extended to N supercapacitors just by adding $SW2$, $SW3$, and $SW4$ in a modular structure. Similarly, the switch array can be applied to the C_{in} selection circuit. The value of C_{in} is related to the amount of ripple at the input stage (I_{ambi}), the charging rate of supercapacitors, and the switching frequency of the charge pump.

IV. SYSTEM PERFORMANCE ANALYSIS

We designed the proposed charge pump based charging circuit using Cadence. We validated and analyzed its performance

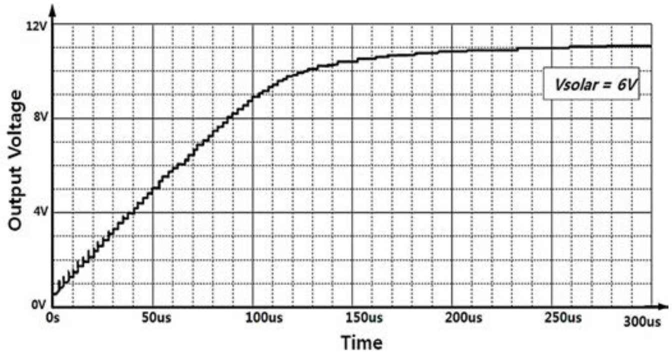

Fig. 7. Boost-up voltage of the Charge pump.

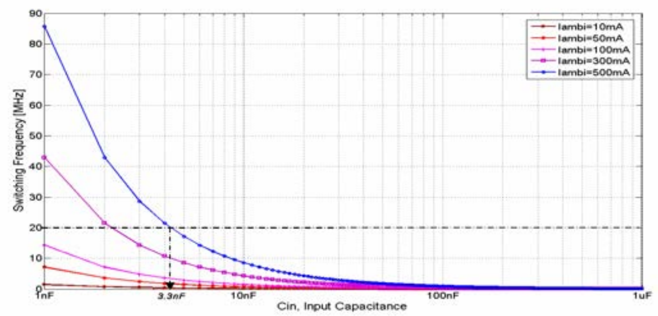

Fig. 8. Variation of switching frequency for different C_{in}

by simulation using Spectra and Matlab Simulink.

A. Performance Analysis of the Charge Pump

The voltage doubler circuit as mentioned in Section III-A was simulated, and the performance results are shown in Fig. 7. The simulation used the following parameters: input voltage $V_{solar} = 6$ V, input capacitance $C_{in} = 10$ nF, switching frequency of 200 kHz, and output load capacitance of 1 μF to speed up the transient response. The result approached steady state quickly, and there was scarcely any undershoot due to accurate non-overlapping operation of the driving clock circuits.

B. Input Capacitor Selection

The value of the capacitor at the power intake, C_{in}, is a key parameter to control the efficiency and the amount of ripple. Assuming the current from the ambient energy sources is relatively constant, the charging time of the input capacitor is proportional to its value capacitance. Also, this charging time depends on the pumping frequency, which affects the charging efficiency.

For instance, if the amount of current inflow from the ambient power source(s) is large, then the fully charging time of the input capacitor is decreased. In this case, if the switching frequency of the charge pump is slower than the charging time of the input capacitor, then the surplus current would be a power loss. Otherwise, if the switching frequency of the charge pump is faster than the fully charging time of the input capacitor, then the charged energy at the input capacitor is transferred to the output capacitor, with a small amount of current. As a result, the charging efficiency is degraded. Simulations have been used to analyze the figures of merit.

As shown in Fig. 8, the lower C_{in} leads to the higher switching frequency, which will cause additional power consumption. Furthermore, since the non-overlapping switching operation would work as a small perturbation on the input power supply line, the capacitor with low equivalent series resistance (ESR) is needed in order to reduce ripple noise. Therefore, determining C_{in} is a crucial factor in terms of charging efficiency and power loss.

C. Charging time comparison depending on Supercapacitors connection

Since the smart switch array is helpful in reducing leakage rate of the supercapacitors through energy balancing technique in Section III-C. In this section, we focus on describing the impact of applying the smart switching array to RSA on the charging time. The simulation was carried out between a single supercapacitor and two supercapacitors in series under sufficient ambient power condition. The different parameters between the two connections are the ESR and voltage of the supercapacitors. In case of series connection, the ESR and the voltage value are twice compared with the single supercapacitor. In general, there are several different parameters between supercapacitors and capacitors: self-discharging rate, leakage rate, and charge distribution. However, during charging phase, we can ignore the effect of charge distribution, while the other two can be reflected on the charging circuit efficiency. Therefore, in short, we used the first-order differential equation of RC circuit for this comparison. The first-order differential equation of RC circuit is given by:

$$v(t) = v(\infty) - [v(0) - v(\infty)]e^{-\frac{t}{\tau}} \quad (2)$$

where $v(0)$ = the initial voltage, $v(\infty)$ = IR = finial voltage, and τ = RC. Also, R is the equivalent value of the charging circuit, and thus it consists of equivalent resistor (R_{eq}) of the charging circuit and ESR (R_{scap}) of the supercapacitor. Also, current I is equal to I_{MPP}. Substituting these parameters into Equation (2),

$$v(t) = v(0)e^{-\frac{t}{(Req+Rscap)C}} + v_{scap}(\infty)[1 - e^{-\frac{t}{(Req+Rscap)C}}]. \quad (3)$$

The supercapacitor ESR (R_{scap}) is in the single-digit milliohm range, so we can ignore it, and R is equal to R_{eq}. We can calculate the value of R_{eq} by fitting this equation to the experimental curve in Figure 9 of [8]. The value is $R_{eq} = 10\Omega$. In [8], a 50F, 2.7V supercapacitor was employed to plot the charging time curve. For the purpose of comparison, we also use C = 50 F, 2.7 V supercapacitor for the simulation. Therefore, $\tau = 500$ seconds $(R \times C = 10 \times 50)$ for a single supercapacitor, while τ for two supercapacitors in series is 250 seconds $(R \times C = 10 \times 25)$. In addition, in case of series connection, the capacitance is reduced by half, $C = 25$ F but the voltage is doubled, at 5.4 V. As a result, the two equation

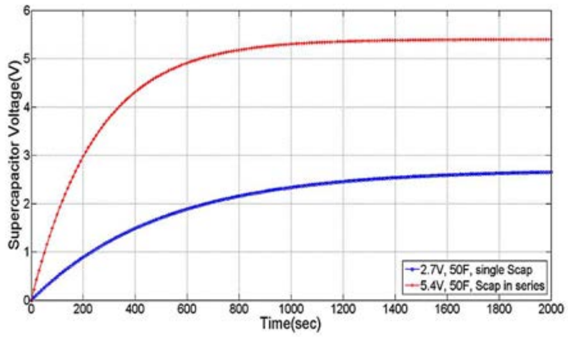

Fig. 9. Comparison of voltage over time for charging supercapacitors.

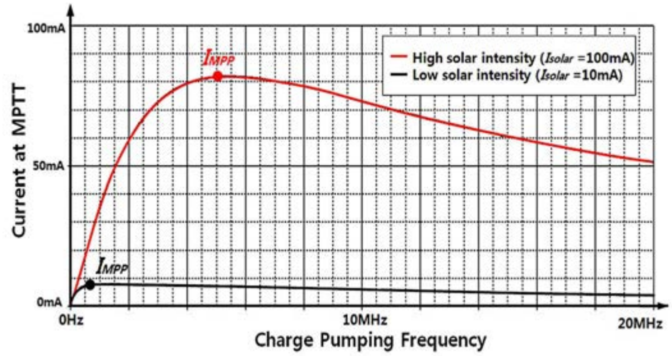

Fig. 10. Sweeping Frequency and Current for MPTT.

can be yielded:

$$v(t)_{25F,single} = 2.7 \times (1 - e^{-\frac{t}{500}}) \quad (4)$$

$$v(t)_{50F,series} = 5.4 \times (1 - e^{-\frac{t}{250}}) \quad (5)$$

Fig. 9 reveals that the charging time of supercapacitors in series is faster than that of a single supercapacitor.

D. I-F curve tracing and I_{MPP}

The *I-F curve* was traced under different ambient power conditions, as expressed by different supply currents. The measurement was conducted at the output current from the proposed charging circuit during the charge pump switching frequency sweeping up to 20 MHz. As shown in Fig. 10, we can see that the system's MPP exists at a certain frequency, and the position of I_{MPP} is shifted depending on the ambient power input conditions.

In more detail, the MCU commands the DDS to sweep the switching frequency for the charge pump, while at the same time, an analog-to-digital converter (ADC) records the output current value and traces its curve. From this curve, the MCU can determine I_{MPP} and adjust the operational switching frequency using the measured I_{MPP}.

As mentioned in Section II-B1, if the supercapacitors are initially in empty state, they can appear as a short circuit. Under this condition, the supercapacitor will be charged very slowly. Therefore, we need to avoid this conditions. Fortunately, the charge pump scheme provides us with a good solution to prevent this kind of short circuit condition. From Fig. 10, we can recognize that the output current from the charge pump can be adjusted by controlling the switching frequency. In other words, when a charge cycle is initiated, the MCU can trace the *I-F curve* and decide the start frequency below the frequency of I_{MPP} and slowly approach the frequency of I_{MPP} by monitoring both I_{ambi} and I_{output}.

V. Conclusion

This paper describes a supercapacitor charging circuit for an energy harvesting system. A voltage doubler charge pump is used to boost up the ambient energy sources to a level that is efficient for supercapacitor charging in terms of lower power loss and faster charging time.

An MPTT scheme that considers the maximum efficiency tracking of the charging circuits is implemented in Cadence and simulated using Spectra and Matlab Simulink. Through the simulation, the feasibility of our MPTT circuit is validated, and the charge pump switching frequency range of up to 20MHz can cover the wide dynamic range of various ambient sources. Thus, considering system complexity and commercial availability, a DDS represents one of the best solutions for controlling the frequency of the charge pump, compared to a conventional analog oscillator, which has a much more limited range. Furthermore, soft charging starting function is helpful to prevent short circuiting of supercapacitors in empty state.

Smart switch arrays are not only able to improve the charging rate of supercapacitors by controlling the serial and parallel connection topology, but they are also easily extendable to multiple energy storage elements. The simulation results confirm the feasibility of our system design. In future work, we will focus more on the system implementation and validate its benefits by more experiments involving real-world applications.

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