Energy Harvesting by Sweeping Voltage-Escalated Charging of a Reconfigurable Supercapacitor Array

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***Abstract*—EscaCap is an energy harvester that uses a boost-up charge pump to perform maximum power-transfer tracking (MPTT) while charging a reservoir supercapacitor array (RSA) with a reconfigurable topology. Unlike buck-down type harvesters, the voltage-doubling charge pump of EscaCap enables the sensor nodes to operate under low ambient power conditions. The supercapacitors in the RSA 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, the RSA of EscaCap is modular and can be easily expanded. Experimental results show that EscaCap can harvest energy efficiently under low and high solar irradiation conditions, achieve shorter charging time, and demonstrate flexibility and robustness.**

I. Introduction

Energy harvesting systems ("harvesters") have been receiving growing attention in recent years, from grid-tied roof-top solar arrays to portable solar chargers for cell phones. Several recent features distinguish embedded-grade, micro-harvesters from their utility-grade, larger counterparts, including emphasis on *low overhead* in maximum power point tracking (MPPT), and the use of *supercapacitors* as a potential type of energy storage elements (ESE).

A. Low-Overhead MPPT

MPPT is the task of finding the load level that maximizes the harvested power as the supply condition varies over time. Due to the non-ideal characteristics of the sources such as solar panels, the maximum power point (MPP) shifts as a function of the load on the family of I-V curves defined by the light intensity and temperature. A harvester that performs MPPT can acquire more power than one that does not, by as much as an order of magnitude. However, MPPT overhead can easily dominate or exceed the harvested power especially for micro-harvesters, and MPPT may require additional circuitry and control. For this reason, either MPPT is not performed in micro-harvesters, or they emphasize low overhead by trading in tracking accuracy [1]–[4]. A recent approach refines the idea of MPPT into maximum *power-transfer* tracking (MPTT) by considering the overhead in the charging circuitry [5].

B. Supercapacitors

In recent years, supercapacitors have been receiving growing interest as energy storage in addition to or instead of batteries in energy harvesting systems. Supercapacitors, also known as ultracapacitors, have extremely long life cycles and have been identified as a promising type of ESE to compensate for or overcome the limitations of batteries. The advantages of supercapacitors include more than one million recharge cycles, high charging and discharging efficiency, and eco-friendly materials. Their energy density has reached a level that makes them practical as ESEs. However, supercapacitors cannot be used as drop-in replacements for batteries without considerations for charging and discharging characteristics.

Given that the energy density of supercapacitors is lower than that of batteries by an order of magnitude, it may be desirable to maximize the capacitance rating of the supercapacitor. Charging a nearly depleted supercapacitor can cause *inrush current*, an effective short circuit when the load is a nearly empty supercapacitor. Although one may place a current limit on the supercapacitor, doing so may be either incompatible with MPPT or significantly lengthen the charging time. Also, since the voltage is linearly proportional to the charge level, the larger the capacitance, the more the unusable stored charge there is below a minimum usable voltage level of the target embedded system. A related problem is *cold booting* [4], where the low voltage (as a result of high capacitance) near the usable threshold can cause futile cycles of repeated booting and exhaustions, despite the otherwise sufficient stored energy.

To address the problems with single supercapacitors, reservoir supercapacitors arrays (RSA) were proposed [2], [4]. In particular [4], a *bootstrap supercapacitor*, which has relatively smaller capacitance than that of the primary ESE, 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 [6], serial discharging becomes inefficient. Besides, previous buck-type charging circuits [1], [3], [4] 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.

C. Solution: Sweeping Charge Pump with Reconfigurable RSA

To address all these issues, we propose a new harvester named EscaCap. For charging, it incorporates a frequency-programmable charge pump circuit to limit inrush current while performing MPTT without perturbation. The charge pump also eliminates the bulky inductor.

For both charging and discharging, it dynamically reconfigures the topology of the RSA. To improve discharging efficiency, EscaCap configures the RSA to compose in series, in parallel, or as singles to maximize the DC-DC converters' efficiency, depending on the load and the supercapacitors' voltages. This approach is simple, flexible, highly efficient, and easy to implement with commercial off-the-shelf (COTS) components. Moreover, since the MPTT technique is independent of the ambient power sources, it can be applied to different types of ambient power sources simply by connection to an input power port of EscaCap.

II. Related Work

We survey related work on micro-harvesters for wireless sensors. The majority of them assume solar panels as the energy source with a peak load level of around 100 mW, though we aim to extend it to as much as 1500 mW for our application. All harvesters surveyed here use some form of ESE, including batteries [7], supercapacitors [2]–[4], [8]–[10], and hybrid [11]. In this section, we compare the supercapacitor topology, MPPT methods, and cold booting support.

A. Supercapacitor Size and Topology

A number of harvesters use supercapacitors in different sizes and topologies. Among those that use a single supercapacitor, those with smaller ones (around 1 F) [8], [10] can charge faster but cannot sustain too many days without sunlight, whereas those with higher capacitance (50-100 F) [3], [9] have a larger amount of unusable charge below the DC-DC converter's threshold voltage. To enable fast recharge to a usable level while supporting large supercapacitors, DuraCap [4] uses a combination of a small-capacitance bootstrap capacitor (bootcap) with an array of larger reservoir supercapacitors. It prioritizes the bootcap so that the system can get started quickly, and then it charges the larger reservoir capacitors sequentially to store the rest of the charge. Our work improves on DuraCap by charging and discharging in different topologies to maximize efficiency and minimize leakage.

B. MPPT for Micro-Harvesters

One way of classifying MPPT for micro-harvesters is whether they require perturbation. Perturbation entails temporarily disconnecting the solar panel from the load and measuring the open-circuit voltage (V_{oc}) or short-circuit current (I_{sc}) [9]. During this time, the circuit must be powered entirely with the stored energy.

To avoid perturbation, one can use the output of a light sensor [2] or a *pilot cell*, which is a miniature solar panel in the size of a photo diode [3], as an approximated V_{oc}. This also has the potential advantage of enabling simple, autonomous analog control without a microcontroller. However, photosensors consume additional power, while pilot cells are extra components that add to the cost of the harvester. In either case, the sensor value may not be representative of the solar panel's condition.

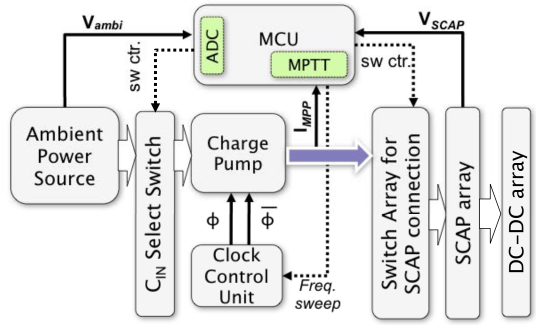


Fig. 1. System block diagram.

C. Cold Booting

Cold booting is the condition of starting a system with little or no charge in the supercapacitor. Ambimax's [2] feedback regulator used for charging the supercapacitor will respond to inrush current by duty cycling it at a very low rate that is incompatible with MPPT. Everlast [9] addresses the inrush-current problem by using a feed-forward regulator instead, but it does not inhibit booting. Solar Biscuit [8] and TwinStar [10] use software control and hardware control (Schmitt trigger), respectively, to inhibit futile booting until sufficient energy has been accumulated, but neither performs MPPT, and the inhibiting delay may grow too long for supercapacitors of large capacitance values. DuraCap [4] solves the delay problem by using a separate supercapacitor for booting, independent of the reservoir ones. Our contribution over DuraCap is to optimize the charging and discharging efficiency of these multiple supercapacitors during cold booting and other charging conditions.

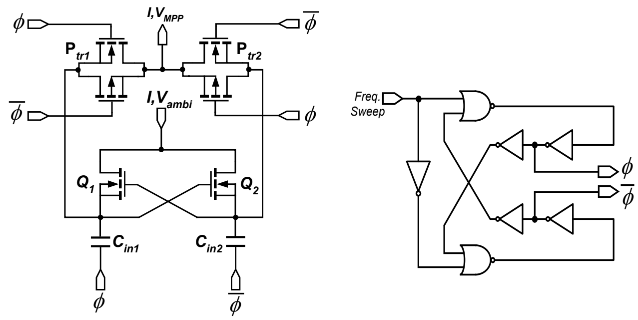
III. EscaCap System Overview

Fig. 1 shows the system block diagram of the EscaCap platform, a self-configuring system with a modular supercapacitor structure. It consists of three subsystems: a boost-up charger with MPTT, a dynamic reconfigurable switch array (DRSA), and a reservoir supercapacitor array (RSA), all controlled by a microcontroller unit (MCU). EscaCap provides 3.3 V and 5.0 V output and supports charging from USB bus power in addition to the solar panel.

The four primary tasks in our proposed energy harvesting method are 1) sensing the voltage from ambient power source(s) and selecting suitable input capacitance C_{in}, 2) sweeping the switching frequency of the charge pump and tracking I_{MPP} on the *I-F curve*, 3) reconfiguring the DRSA to optimize the input capacitors or connect the RSAs in series or as single cells, and 4) charging the selected supercapacitor(s) at I_{MPP}.

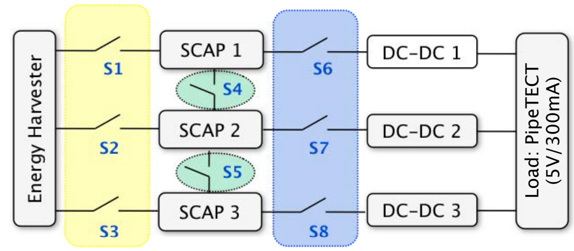
A. Boost-up Charge Pump

According to Sokal [12], the fastest and most efficient method to charge a capacitor is to use the maximum switching current. Therefore, the charge pump with its pulsed current output is a good way to charge supercapacitors. A charge pump

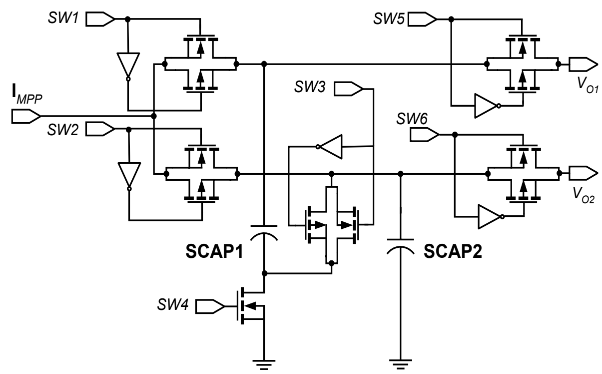


(a) Charge-pump Cell (b) Non-overlapping Clock

Fig. 2. Charge Pump Configuration



(a)



(b)

Fig. 3. Dynamic reconfigurable switch array (DRSA): (a) block diagram for three supercapacitors, (b) schematic for two supercapacitors

converts an input voltage to one higher than the supply voltage. Fig. 2 shows how this is possible using the voltage doubler charge pump cell, as they merely require two extra capacitors, with no need for any additional inductors.

Signals ϕ and $\overline{\phi}$ are a pair of non-overlapping clocks that are 180° apart. During clock phase $\overline{\phi}$, Q_1 closes to connect the I_{ambi} to the top plate of $C_{\text{in}1}$ and the bottom plate of $C_{\text{in}1}$ is connected to 0 V to charge $C_{\text{in}1}$; at the same time, Q_2 opens to disconnect the I_{ambi} from the top plate of $C_{\text{in}2}$ and the bottom plate of $C_{\text{in}2}$ is connected to V_{ambi}. This way, the top plate of $C_{\text{in}2}$ is boosted to $2V_{\text{ambi}}$. During clock phase ϕ, the operation of the charge pump works in a similar way.

After a few clock cycles, the clock signals on the top plates of the capacitors will assume an amplitude of $2V_{\text{ambi}}$. The switches $P_{\text{tr}1}$ and $P_{\text{tr}2}$ are timed, so that V_{out} at the output of the charge pump sees this voltage. The charge pump requires a non-overlapping and two-phase clock generator as shown in Fig. 2(b).

B. MPTT using Frequency Sweeper

Because charging circuit efficiency is a function of the load, maximum *power-transfer* tracking (MPTT) was proposed to consider the efficiency of the charging circuits [5]. To realize MPTT, we adapt a charge pump to charge the supercapacitors. We utilize a programmable oscillator to cover the wide frequency sweeping range of the charging circuit that tracks the wide dynamic range of the ambient power source.

Fig. 1 shows how MPTT is implemented in EscaCap. The sudden change of V_{ambi} triggers the frequency sweeper to start finding I_{MPP}. The current prototype detects this change in software, but hardware comparators can also be used to detect this change. The MCU sweeps the frequency range to find I_{MPP} and sets the corresponding charge-pump frequency. By giving a series of pumping frequencies, the charge pump transfers the harvested energy to the supercapacitors. This MPTT method is perturbation-free and can be realized without additional components.

C. Dynamic Reconfigurable Switch Array (DRSA)

The design objective of the DRSA 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's voltage and prevents overcharging above the rated voltage by reconfiguring the switch array. Fig. 3(a) shows the block diagram for how three supercapacitors can be connected by the switch array, and Fig. 3(b) shows the schematic for two supercapacitors.

1) Charging Phase: Fig. 3(b) shows an example of the DRSA 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 as well as equivalent series resistance (ESR) but half the capacitance as a single supercapacitor. As will be shown in Section IV-D, charging two supercapacitors in series is more efficient (faster, less loss) than charging a single one by 9%. In case the supercapacitors in series composition are not of the same capacitance, then we need to monitor V_{SCAP1} and V_{SCAP2} individually and control the DRSA to prevent charging over their rated voltage (2.7V). In the case when the ambient power is scarce, the MCU reads V_{SCAP1} and V_{SCAP2} and decides to charge the supercapacitor with a lower voltage, one at a time, because the leakage rate is exponentially proportional to the supercapacitor voltage [6]. Therefore, it would be more efficient to charge the supercapacitor at a lower leakage rate by using the small amount of harvested energy.

2) Discharging Phase: The DRSA also helps improving the efficiency at the output stage of the harvester. Most micro-harvesters are designed for traditional wireless sensor nodes

TABLE I
A SET OF SWITCH ARRAY CONNECTIONS FOR FIG. 3(B). 1 = CONNECTED, 0 = OPEN.

Connection Status	$SW1$	$SW2$	$SW3$	$SW4$	$SW5$	$SW6$
Charging S_{CAP1}	1	0	0	1	0	0
Charging S_{CAP2}	0	1	0	1	0	0
Charging in series	1	0	1	0	0	0
Charging in parallel	1	1	0	1	0	0
Discharging in series	0	0	1	0	1	0
Discharging in parallel	0	0	0	1	1	1

that consume 100-150 mW. For example, the Mica2 can run at 3.3V/45mA; the iMote at 2.5V/60mA; and the Eco node at 3.3V/20mA. However, applications that require more local processing, high-duty sensing, or more powerful RF [13], [14] demand power on the order of 5V/300mA.

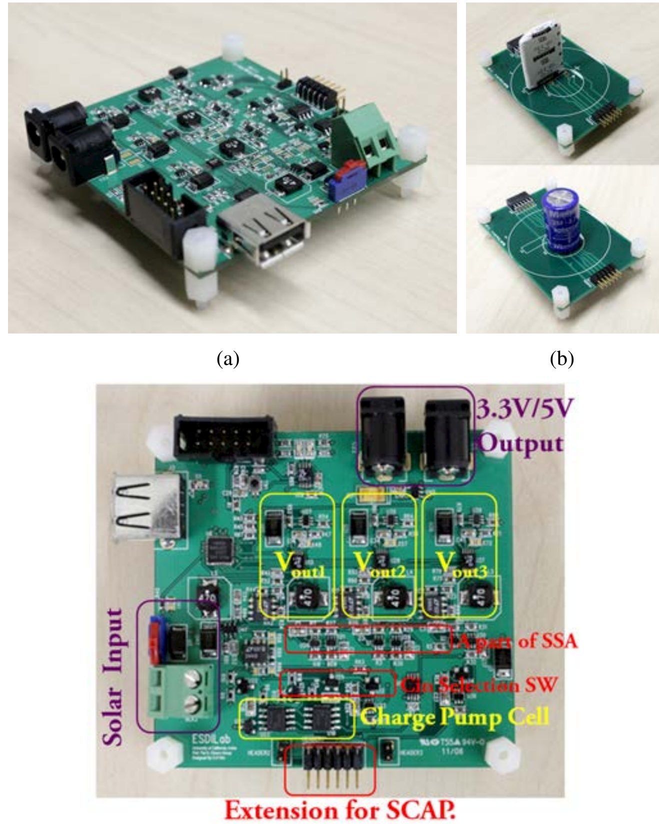
In contrast with voltage range of (lithium) batteries (3.7 $\sim$ 4.2V), supercapacitors have a voltage range of 0V to 2.7V, and therefore step-up DC-DC converters are required to supply power to most wireless sensor nodes. However, most COTS DC-DC converters are optimized for rechargeable batteries rather than supercapacitors. Assuming the nodes can operation at 3.3V/45mA (e.g., Mica2), if the input voltage of the battery is 2.4V, then the discharging efficiency is 93% in PFM mode. In contrast, if the nodes can operation at 5V/300mA as in high-duty nodes, when the input voltage of supercapacitors is 1.2V, then the discharging efficiency is 78% in PWM mode [15]. In addition, since the minimum input voltage of COTS DC-DC converters is 0.7V, even if supercapacitors were charged up to 0.7V, this charged energy could be wasted due to minimum voltage of COTS DC-DC converters.

The DRSA can address these issues. For instance, suppose all output voltages of three supercapacitors are 0.8V. If the DRSA connects the supercapacitors in series, then the output voltage will be 2.4V, and therefore the net efficiency of the DC-DC converter will be increased to 93%. This way also allows us to use the residual energy ($\leq$ 0.7V) of supercapacitors effectively.

The combinations of switching connection based on Fig. 3(b) are shown in Table I. The DRSA can be easily extended to N supercapacitors, as limited by the number of GPIO pins, just by composing a set of switches and a single supercapacitor in a modular structure.

D. Implementation

Fig. 4 shows photos of a prototype of EscaCap. The RSA can be extended by plugging additional supercapacitor modules using the extension connectors (Fig. 4(b)). The measured data is transferred to the host computer via USB, which also provides a charging function. The dedicated MCU on EscaCap is the C8051F353, which is rated at 50 MIPS and comes with 8 KB Flash, a 16-bit ADC, 17 GPIO pins, I2C, SPI, UART, 16-bit counter/timers, and an internal oscillator. The MCU connects via SPI to the frequency sweeper to control the switching frequency of the charge pump. It is also possible to replace this MCU with the existing MCU of the wireless sensor node, for example.



(a) (b)

(c)

Fig. 4. (a) EscaCap prototype (b) supercapacitor modules (c) top view

LTC6900 is a low-power, high-precision, programmable oscillator. Its frequency range is from 1kHz to 20MHz, allowing it to cover the wide dynamic range of the ambient power sources. The single output feeds the non-overlapping clock controller to generate the two clock signals 180° apart.

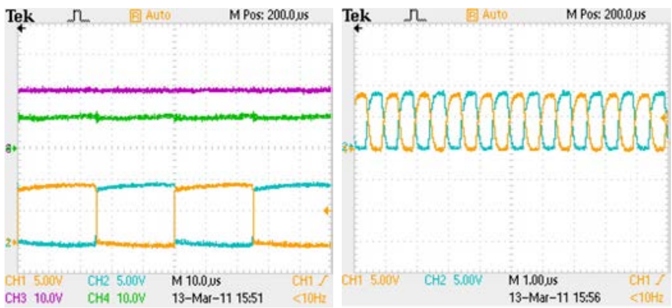
The MOSFET for a charge pump is required for high-speed on/off switching and for high input voltage and current. Since the mobility of electrons is faster than that of holes, N-type MOSFET is more suitable for high-speed switching operations. FDN357N is a good component for this purpose, because it has fast switching time and low in-line power loss. However, the switch array uses the load switch with level-shift (SI1869DH) as a reconfigurable power path switch. It contains both P- and N-channel MOSFETs in the same package.

IV. EVALUATIONS

A. Experimental Setup

To validate the functions of EscaCap, we conducted experiments using a daylight lamp in an indoor environment. The lamp is set to emulate the low sunlight irradiation in order to show the advantages of the charge pump scheme. The measured sunlight intensity is < 100 W/m^2 (7am or 5pm in February in Irvine, California, USA), which is low compared to 150-300 W/m^2 (9am) and over 1200 W/m^2 in the early afternoon. We utilize a 10VDC/2.5W monocrystalline

Fig. 5. Measured Solar panel I-V curve.



(a) Measured boost-up (b) Non-overlapping clocks @1MHz

Fig. 6. Measurement of charge-pump operation.

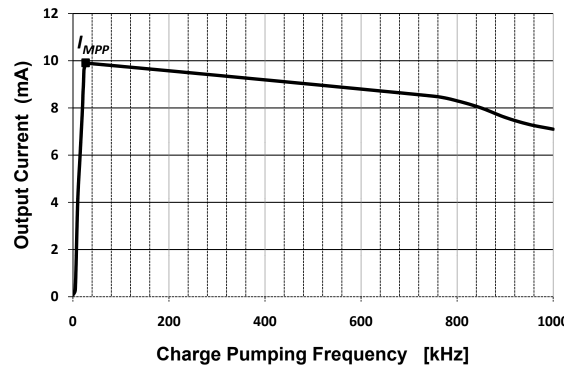


Fig. 7. Sweeping Frequency and Current for MPTT.

solar panel (XP645D) and measured the characteristics of the solar panel under the aforementioned low light intensity condition. Fig. 5 shows the measured solar I-V curve. With this experimental setup, input capacitance (C_{in}) was fixed at 1 μF, and frequency sweeping was conducted from 1 kHz to 2 MHz.

B. Boost-up Operation of the Charge Pump

The boost-up operation is useful to harvest the energy under low solar irradiation conditions. There are two types of boost up converters: step-up buck converters and charge pumps. Charge pumps are better for meeting the size constraint of energy harvesters. We experimented with the boost-up operation of EscaCap and show the results in Fig. 6. The purple line shows the boost-up output voltage (17.2V avg.) of a charge pump, and the green line indicates the solar input voltage (9.8V avg.). The non-overlapping clock, which was implemented using the LTC6900 programmable oscillator with the circuit shown in Fig. 2(b), has great influence on the performance of the charge pump. Fig. 6(b) shows non-overlapping clocks at 1MHz with 9.8V input voltage from the solar panel.

C. I-F Curve Tracer

Frequency sweeping is a crucial function to cover the wide dynamic range of ambient power sources. However, it could be additional overhead. The LTC6900 is a low-power programmable oscillator, which can sweep frequencies of up to 20 MHz. The *I-F curve* was traced under low solar irradiation conditions. The MCU (C8051F353) records the current value at the output path of the (charge pump) charging circuit. Therefore, it performs MPTT by considering the efficiency of the charging circuit.

In more detail, the MCU commands the LTC6900 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 measure I_{MPP} for adjusting the operational switching frequency. In the typical operating range, the circuitry incurs overhead of about 1.5mW according to our measurement.

As mentioned in Section I-B, if the supercapacitors are initially in empty state, they can appear as a short circuit, which can be far from the MPP. Fortunately, the charge pump scheme provides us with a good solution to prevent this kind of short circuit condition. From Fig. 7, we can recognize that the output current from the charge pump can be adjusted by controlling the switching frequency. In other words, the MCU can find the new I_{MPP} as follows: starting from the switching frequency of just below the previous I_{MPP}, sweep the *I-F curve* by monitoring both I_{solar} and I_{charging}.

D. Charging Time: Single vs. In-Series

The DRSA is helpful in reducing the leakage rate of the supercapacitors through an energy balancing technique. In this section, we focus on describing the impact of applying the DRSA to RSA on the charging time. The experiment was carried out between a single supercapacitor and two supercapacitors in series under relatively low solar irradiation of ≤ 100 W/m^2.

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 those of a single supercapacitor. However, the supercapacitor ESR (R_{scap}) is in the single-digit milliohm range, and a charge pump can handle twice the voltage value in case of series connections. So, it is more advantageous in reducing the charging time of supercapacitors, because in case of series connection, the capacitance is reduced by half. We conducted the experiment using 150F/2.7V supercapacitors (BCAP0150 P270) made by Maxwell Technologies.

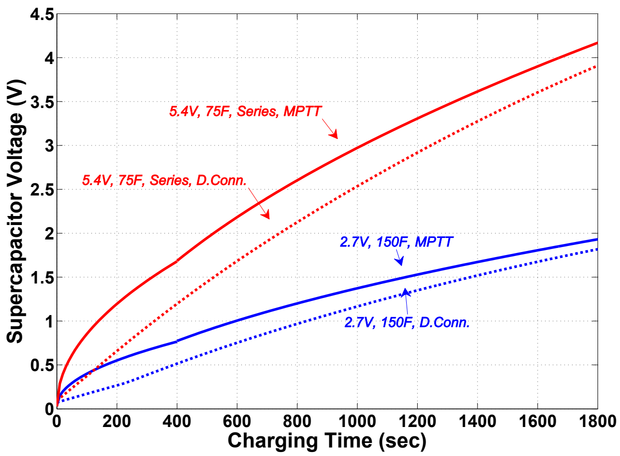


Fig. 8. Measured voltage over time for charging supercapacitors with solar power from Fig. 5. Solid lines: MPTT; dotted lines: no MPTT; red (upper two curves): two in series; blue (lower two): single supercapacitor.

Fig. 8 shows the measured charging times of a single supercapacitor and of two supercapacitors in series connection. The dotted lines represent the charging behavior without MPTT (i.e., directly connecting the solar panel to the ESE), while the solid lines show those of the proposed MPTT method, all under the same low solar irradiation of Fig. 5. It is more efficient to charge two supercapacitors in series than one in parallel: a single supercapacitor takes 1800 seconds to charge up to 2 V (300 J) while the pair in series takes 1650 seconds to charge up to 4 V (also 300 J) under the same condition. In summary, charging the pair in series with our MPTT is 9% faster than either charging the same pair without MPTT or charging a single supercapacitor with MPTT.

V. Conclusion and Future Work

This paper describes the EscaCap energy harvesting system. The charge pump enables more efficient charging of supercapacitors in terms of lower power loss and faster charging time. The reconfigurable supercapacitor topology enabled by the DRSA further improves the charging and discharging efficiency over different solar irradiation levels and load levels. The charge pump in conjunction with a programmable oscillator supports MPTT, i.e., MPPT with after charging circuits. Experimental results validated the benefits of dynamic topology and MPTT under low and high solar irradiation conditions. It is also easily expandable to multiple ESEs.

Future work includes system-level optimizations, better cold-booting support, and real-world evaluations. The dedicated MCU can be eliminated by moving its functions to an existing MCU, such as the one on a wireless sensor node. It will save component cost while adding little software overhead, especially if the MCU is underutilized in the first place. We also plan to add (nonvolatile) programmable voltage comparator hardware to not only help reduce software overhead in tracking but also enable autonomous cold-booting without MCU intervention. We are planning long-term deployment of the improved design for a remote monitoring application for water pipes with high duty-cycle requirements [14], [16].

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