DuraCap: a Supercapacitor-Based, Power-Bootstrapping, Maximum Power Point Tracking Energy-Harvesting System

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ABSTRACT

DuraCap is a solar-powered energy harvesting system that stores harvested energy in supercapacitors and is voltage-compatible with lithium-ion batteries. The use of supercapacitors instead of batteries enables DuraCap to extend the operational life time from tens of months to tens of years. DuraCap addresses two additional problems with micro-solar systems: inefficient operation of supercapacitors during *cold booting*, and maximum power point tracking (MPPT) over a variety of solar panels. Our approach is to dedicate a smaller supercapacitor to cold booting before handing over to the array of larger-value supercapacitors. For MPPT, we designed a bound-control circuit for PFM regulator switching and an I-V tracer to enable self-configuring over the panel's aging process and replacement. Experimental results show the DuraCap system to achieve high conversion efficiency and minimal downtime.

Categories and Subject Descriptors

C.3 [**Special-purpose and application-based systems**]: Real-time and embedded systems

General Terms

Design, Experimentation, Performance

Keywords

Maximum power point tracking, supercapacitors, cold booting

1. INTRODUCTION

Energy harvesting from the environment can significantly extend the operating life of many systems that have no access to utility power. Solar power is one of the most viable sources for energy harvesting. However, batteries inside solar-powered systems often require replacement after a few years. What is needed is a durable, efficient, self-configuring, micro-solar energy harvesting system that can replace rechargeable (e.g., lithium-ion) batteries.

We have designed such a system, named DuraCap. It stores energy not in batteries but in supercapacitors, which are significantly more durable. To be efficient and self-configuring, it performs maximum power point tracking (MPPT) for not only a specific type of solar panel but also for replacement panels of different sizes and types over the system's entire life time. The distinguishing characteristics of DuraCap are as follows.

Fast, Robust Booting It is inevitable that a solar-powered system exhausts all of its buffered energy due to persistent poor weather conditions. When the system must *cold boot*, i.e., start from total exhaustion of energy, it may have to wait until not only when the voltage is high enough but also when it has enough buffered energy to sustain stable operation. The cold booting stage must be considered or else the powered system may suffer from either a long down time or unstable operation.

Self-Calibrated MPPT To operate at high harvesting efficiency levels, MPPT is to adjust the load to match the panel's specific operating point to maximize the amount of power transferred. Macro-solar systems perform MPPT by binary search dynamically, whose overhead may be prohibitive for micro-solar systems. A common solution for micro-solar ones is to look up a statically generated table based on the measured light intensity, load, and possibly temperature. While simple and effective, this static-table scheme is limited to a specific type of panel chosen before deployment. When a panel changes its characteristics over time, or it may need to be replaced due to aging or damage, the MPPT system may no longer work without recalibration, which is often a tedious, manual process. DuraCap implements multiple MPPT methods to keep the harvesting efficiency high over a variety of environments. An enhanced switch for the PFM regulator and a power path switch for the supercapacitor array are designed for low-voltage control, which helps the MPPT system reduce power consumption.

Experimental results show that the bound-control MPPT circuit, the enhanced switch, and the supercapacitor array achieve high conversion efficiency, low power consumption, and long operational life time.

2. RELATED WORK

Heliomote [3] is a wireless sensor node that uses solar panels as its energy source and two AA-type NiMH batteries as its energy storage. Two solar panels connect to the batteries directly through a protection diode without any MPPT circuit. This solution is simple but has two drawbacks. First, the system begins charging only when the solar panel voltage is higher than $V_{BAT}+0.7$ (due to the diode drop), and it must discard all power lower than this relatively high voltage. Second, the $V_{BAT}+0.7$ voltage is much lower than the maximum power point (MPP).

Prometheus [2] uses both a supercapacitor and a Li-Polymer battery as its power buffers. It prioritizes the use of supercapacitor for discharging and charging, thereby slowing down the aging of the

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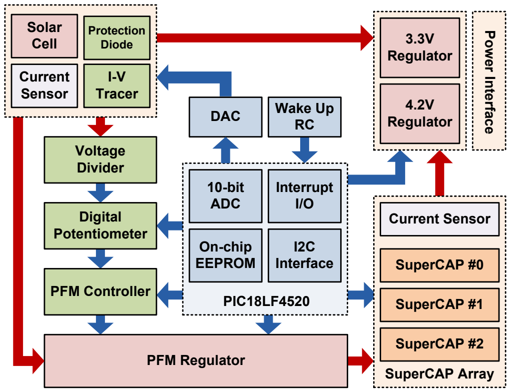


Figure 1: DuraCap system block diagram.

battery. This feature is expected to increase the lifetime of the battery. However, neither Heliomote nor Prometheus performs MPPT.

Because MPPT can be expensive if done precisely, AmbiMax [5] performs approximate MPPT without requiring a microcontroller unit (MCU) to reduce the overhead while accepting multiple ambient energy sources such as solar panel and wind generator. Its MPPT circuit is built with a hysteresis comparator that uses a photosensor or wind speed meter as the reference signal. Although AmbiMax achieves good efficiency, it requires manual calibration each time a new source is used or if the characteristics of the source changes over time. Moreover, AmbiMax suffers from inefficient cold start, because the switching regular views an empty capacitor as a short circuit and thus limits the current to very low, thereby keeping the solar panel operating at inefficient points.

Another solar energy harvester based on a modified AmbiMax architecture uses with a pilot-cell [1], which is a small solar panel that as an active reference input for MPPT instead of a passive photosensor. The advantage of using the pilot-cell is that it does not consume additional power. Although the circuit can charge the supercapacitor from being empty, it relies on the load circuitry to inhibit booting until sufficient energy has been accumulated, or else the system may continue several futile attempts to start up before it runs out of energy again. It also relies on static characterization of the panel.

Everlast [6] is a wireless sensor node with a built-in solar MPPT system that uses a supercapacitor as its only energy storage. Everlast performs MPPT on the same MCU as the sensor node's to execute an MPPT algorithm and drives a series of pulses to control the PFM (pulse-frequency modulation) regulator. An I-V tracer tracks the MPP of the solar panel in a constant-interval time. The harvesting efficiency of the Everlast is much higher than Heliomote and Prometheus. However, the software MPPT requires the MCU to stay active all the time, and this potentially consumes more power.

3. DuraCap SYSTEM DESIGN

DuraCap consists of several parts: solar panel, energy storage, system control unit, power regulator, and MPPT circuitry. DuraCap is designed to be a standalone, self-configuring system. It provides a 4.2V output, which is similar to a Li-ion battery, so that the users can easily replace the battery with DuraCap without changes to the target device. Fig. 1 shows the system block diagram of the DuraCap. The following sections describe the subsystems in detail.

3.1 Solar Panel and Protection

To protect solar panels from the adverse current damage, a diode

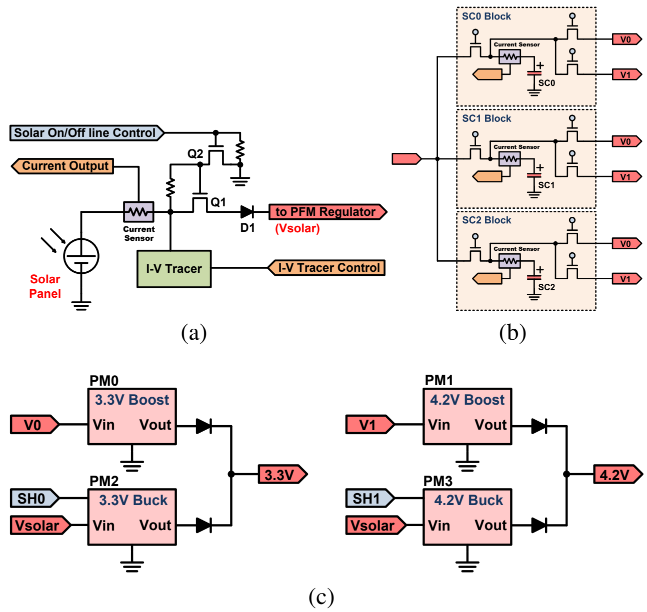


Figure 2: (a) The circuit around the solar panel. (b) supercapacitor array. (c) output power.

$D1$ is added between the solar panel and the system, as shown in Fig. 2(a). Moreover, MOSFETs $Q1$ and $Q2$ are added between the solar panel and the protection diode to build a solar panel on/off line switch. By controlling this switch, the system can isolate the solar panel from the rest of the system when performing I-V curve tracing, to be described in Section 3.4.3.

3.2 Energy Storage

As shown in Fig. 2(b), DuraCap stores harvested energy in three supercapacitors. One is the *booting supercapacitor*, which has the highest charging priority and relative small capacitance compared to the other two, called *reservoir supercapacitors*. The capacitance of the booting supercapacitor should not be too large, so that it can be quickly charged up to enable cold booting; it is also used temporarily during the regular MPPT. On the other hand, the capacitance of the booting capacitor should not be too small, either, because it needs to smooth out unstable supply conditions during cold booting. The two reservoir supercapacitors have large capacitance in order to provide power for the target device. The supercapacitor array is maintained by several switches called the *power path switches*. They are specifically designed to control power flow for charging and discharging of a supercapacitor (Section 3.5.1).

3.3 Power Modules

DuraCap provides two different output voltages: 3.3V and 4.2V. The 3.3V is supplied mainly for the system itself, although it is also available for external use. The 4.2V is similar to that of a Li-ion battery such that many target devices can directly use DuraCap as a power source without modification. DuraCap is able to switch the input source for the regulator between the solar panel and any of the three supercapacitors. Fig. 2(c) shows the block diagram of the power modules in DuraCap: *PM0* and *PM1* convert power from the supercapacitor array, while *PM2* and *PM3* convert power from the solar panel. Both *PM0* and *PM2* output 3.3V while both *PM1* and *PM3* output 4.2V, but only one of the regulators of a given voltage is turned on at a time. To maintain the stable operation, the

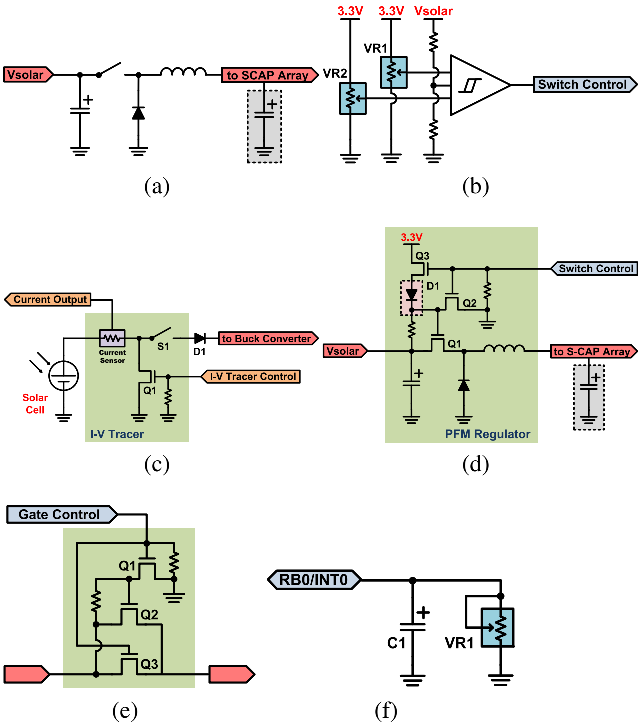


Figure 3: (a) PFM regulator circuit. (b) Bound-control. (c) I-V tracer circuit. (d) The circuit of PFM regulator with enhanced switch. (e) The circuit of power path switch for supercapacitor array. (f) Wake-up circuit for MCU.

system outputs power to the target device only when at least two supercapacitors are available in the reservoir supercapacitors array.

3.4 MPPT Circuitry

3.4.1 *PFM Regulator*

To charge the supercapacitor, DuraCap uses a pulse-frequency modulated (PFM) regulator to transfer the harvested energy, similar to Everlast. The reason is to address a problem with traditional high-efficiency PWM DC-DC converter, which sees the supercapacitor as a short circuit when it is not charged. By giving a series of pulse, the switch in the PFM regulator turns off PFM momentarily so that the voltage of the solar panel remains around the MPP.

Fig. 3(a) shows the circuit of the PFM regulator. It acts as a switched-capacitor circuit since it charges a capacitor and then transfers the energy to the load supercapacitor. Meanwhile, it is similar to a transformation of a buck regulator with the capacitor moved to the front side of the switch. The PFM regulator actually acts as a buck regulator when charging a supercapacitor. The pulse control for a PFM regulator can be done by either an MCU or a bound-control comparator (Section 3.4.2), depending on the MPPT mode. Section 3.5.1 presents details of the switch in the PFM regulator.

3.4.2 *Bound-Control PFM Switching Controller*

The bound-control circuit contains four analog comparators to generate the control signals for the PFM regulator, without requiring the MCU to perform MPPT in software. As shown in Fig. 3(b), the MCU only needs to write to the nonvolatile digital potentiometers *VR1* and *VR2* to set the upper and lower-bound values for the comparators in the bound-control circuit. Then, the PFM regulator will run autonomously even when the MCU is off.

3.4.3 *Solar Panel I-V Tracer*

DuraCap accomplishes MPPT by tracing the I-V curve for the given solar panel. During I-V tracing, the MCU disconnects the solar panel from the system momentarily by turning off the solar panel's on/off line switch. Since the solar panel has to be standalone when performing I-V curve tracing, the system must source its power from the supercapacitor array instead of the solar panel. Fig. 3(c) shows the solar panel's I-V tracer circuit, which consists of an N-type MOSFET $Q1$, the solar panel's on/off line switch $S1$, and a digital-to-analog converter (DAC) IC. The MCU operates the DAC to output a linear change of signal to the gate of the N-type MOSFET, similar to varying the load on the solar panel.

3.5 System Control

3.5.1 *Enhanced Switch*

To save power consumption, DuraCap itself operates at 3.3V, which is a relatively low voltage compared to the input voltage from solar panel. It can be a problem for a common MOSFET to control a high-level power path using a low-level gate signal. To solve this problem, we design two types of enhanced switches for power path control.

Enhanced Switch for PFM Regulator To reduce the rising time of the solar panel, the switch must have fast response time by turning off the switch immediately. To accomplish this, the diode $D1$ is added into the switch, as shown in Fig. 3(d). $Q1$ and $Q3$ are P-type MOSFETs, $Q2$ is an N-type MOSFET, and $D1$ is a Schottky diode. By placing a diode $D1$ between 3.3V and the P-type MOSFET $Q1$, the diode provides a short cut for raising the V_{GS} of $Q1$ starting from 3.3V, and thus the V_{GS} can rise faster and then turn the switch off promptly.

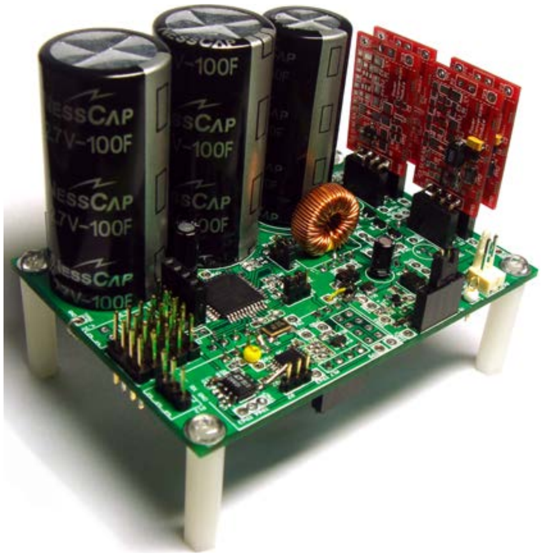
Power Path Switch for Supercapacitor Array Three switches in each of the three unit blocks of Fig. 2(b) are replaced with the power path switch being discussed here. The voltage across the power path switch here ranges from 0V to 2.7V, and it is also the charging and discharging voltage range of the supercapacitor. Fig. 3(e) shows the circuit of the power path switch for the supercapacitor array, where $Q1$ and $Q3$ are N-type MOSFETs and $Q2$ is a P-type MOSFET. When the gate control goes high, both $Q1$ and $Q2$ turn on and enable the path charging to the supercapacitor. Conversely, $Q1$ and $Q2$ turn off the charging path when the gate control goes down.

3.5.2 *MCU*

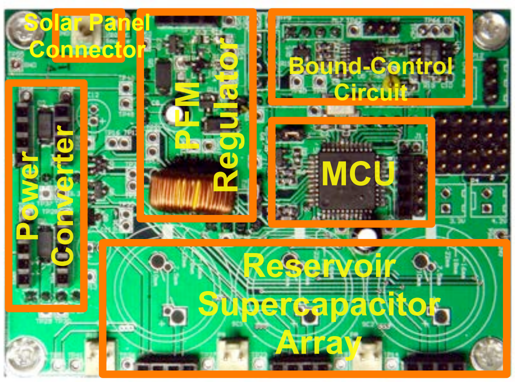
All functions in DuraCap are performed by a low-power MCU. The system uses SPI to control the DAC for the I-V curve tracing. The I^2C interface is used by the MCU to enable the target device to send query commands for the level of available energy in each supercapacitor, among other features. The MCU uses its ADC to detect the voltage value of the solar panel, supercapacitors, and the current sensor output. The PWM controller generates the switching for the PFM regulator to perform MPPT.

3.5.3 *Wake-Up Circuit*

The MCU in DuraCap may sleep at night, during bad weather conditions without sufficient sunlight, or when performing bound-control MPPT. The MCU would have to wake up only once in a while to execute the assigned procedure. The wake-up interrupt delay time depends on the variable resistor value in the RC circuit



(a)



(b)

Figure 4: Photo of DuraCap energy harvesting system (a) side view (b) top view, without the supercapacitors.

shown in Fig. 3(f), where $C1$ has a constant value 100μF, and *VR1*[1] is a variable resistor. In DuraCap, a programmable digital potentiometer is used, hence the MCU is able to configure the resistance to control the delay time of the wake-up interrupt.

4. IMPLEMENTATION

Fig. 4 shows the DuraCap energy harvesting system. It has an area of 8.6×6.3cm^2 including three supercapacitors. A Molex connector on the board connects the solar panel to the system to prevent users from plugging it in reverse.

Solar Panel DuraCap accepts a wide range of solar panel output voltages, from 5.0 to 12.0V with a maximum power transfer of 6W to the system. In this paper, we select a solar cell module whose maximum output is 200mA at 6.0V. The solar panel must have the ability to produce at least the power that DuraCap needs to manage the system.

I-V Tracer A DAC IC implements the I-V tracer, which can be configured via SPI. DuraCap uses the Texas Instruments DAC8311, which is a low-power, single-channel, voltage-output DAC. It supports four modes of operation: normal operation, output 1kΩ to *GND*, output 100kΩ to *GND* and *high-z*. The DAC8311 must operate in *high-z* mode when the I-V tracer is not running to guarantee that the I-V tracer does not affect the solar panel. As DuraCap performs I-V curve tracing, the DAC8311 switches to normal mode to output the assigned voltage.

[1] Same *VR1* name as that in Section 3.4.2 but distinct and unrelated.

Table 1: Regulators arrangement for two output voltages

Power Source	4.2V	3.3V
Solar Panel	LTC1779	LTC1779
Supercapacitor	LTC3400	LTC3525ESC6-3.3

Digital Potentiometer DuraCap uses the MAX5478 from Maxim-IC, a 256-tap, non-volatile digital potentiometer with I^{2}C. Its maximum resistance is 100kΩ.

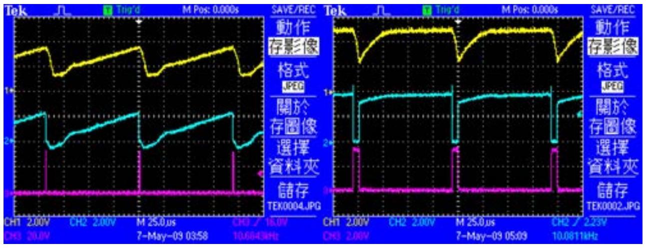
Current Sensor DuraCap uses the MAX9928 from Maxim-IC, a micro-power, bidirectional current-sense amplifier. It has a wide input common-mode voltage range of -0.1 to 28.0V and is independent of supply power. It senses voltage from the R_{SENSE} and outputs a current to the other side with a ratio of 5μA/mV. An external resistor converts the output current to a voltage, allowing an adjustable gain so that the voltage can be matched to the maximum ADC input of the MCU.

MCU DuraCap uses the Microchip PIC18LF4520, a low-power, 8-bit MCU with 32 KBytes of flash program memory, 1536 bytes of data SRAM, and an on-chip, 256-byte EEPROM data memory. It contains 36 GPIO pins, a 13-channel 10-bit ADC, PWM, UART, SPI, I^{2}C, an 8-bit timer, and three 16-bit timers. Two serial interfaces, SPI and I^{2}C, connect the digital-to-analog converter (DAC) and digital potentiometer, respectively.

Supercapacitor DuraCap uses the pseudo series supercapacitors from PAC Electronics [4]. They have a maximum voltage of 2.7V. Totally three supercapacitors are used in DuraCap. The booting supercapacitor in DuraCap has a capacitance value of 50F, compared to 200F for each of the reservoir ones. It occupies a layout area of 18×18mm^2 and 40mm in height and provides up to 182.25J of energy. Each reservoir supercapacitor occupies a layout area of 22×22mm^2 and 45mm in height. When fully charged, the reservoir supercapacitors can supply 1458J of total energy.

Comparators in Bound-control Circuit DuraCap uses the National LM339, which contains four voltage comparators in a single package. It has supply voltage in the range of 2.0 to 36.0V. A pin-compatible alternative to LM339 is the TLC3704 from Texas Instruments. The TLC3704 has lower I_q of 0.02mA for each channel, compared to 0.2mA for the LM339.

Power DuraCap supplies both 3.3V and 4.2V for its own operation and to the target device. Four switching regulators are needed for the two power supplies shown in Fig. 2(c). Table 1 shows the arrangement of regulators in DuraCap. LTC3525ESC6-3.3 is a micro-power, 400mA step-up DC-DC converter with an input voltage range of 0.85-3.3V and an output voltage of 3.3V. It has high efficiency of over 90% on average. LTC3400 is a micro-power, 600mA boost converter with an output range of 2.5-5.0V. The LTC3400 is placed in DuraCap to boost the voltage to up to 4.2V from the supercapacitor's 0-2.7V. LTC1779 is a current-mode, 250mA step-down DC-DC converter with a wide input range of 2.5-9.8V. The LTC1779 has an under-voltage lockout feature that shuts down the LTC1779 when the input voltage falls below 2.0V. DuraCap enables the LTC1779 to convert power from the solar panel when the supercapacitors are empty and supplies 3.3V of power to the system.



(a) (b)

Figure 5: (a) measured signal without enhanced switch. (b) with an enhanced switch for PFM regulator.

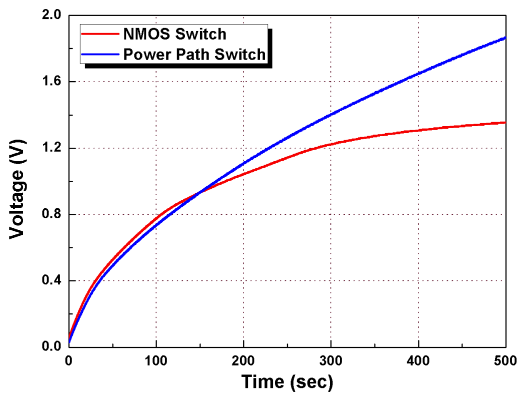


Figure 6: Charge curve comparison between power path switch and NMOS switch.

5. EVALUATION

5.1 Experimental Setup

To validate the function of DuraCap, a stable and repeatable experimental environment is required. For this reason, the experiments are performed in an indoor environment with a controllable emulated sunlight source instead of a variable sunlight source in an outdoor environment. A halogen lamp is set to emulate the sunlight with a maximum light output level of over 900 lumens.

To monitor the status of the components in DuraCap, we developed a measurement system that consists of two parts: measurement hardware station and PC host measurement GUI. The measurement hardware uses the Microchip dsPIC33FJ256GP710 controller. It has a 32-channel 12-bit ADC module of up to 500k samples per second. The measurement base station transfers the measured data to the PC host via UART at 115200 baud. The PC host measurement GUI is written in the Python language. The channel number to be monitored is configurable by modifying the configuration file. For monitoring DuraCap, five physical channels are required: one for the voltage of the solar panel V_{solar}, one for the current of the solar panel I_{solar}, and three for the supercapacitors.

5.2 Experimental Results

5.2.1 Enhanced Switch

The experiments presented here validate the functionality of the enhanced switch for the PFM regulator (Fig. 3(d)) and the power path switch for the supercapacitor array (Fig. 3(e)), as described in Section 3.5.1.

Enhanced Switch for PFM Regulator Fig. 5 shows the signal comparison between using and not using the enhanced switch. *CH1* (top, yellow) is for the solar panel voltage V_{solar}, *CH2* (middle, light blue) is for the gate voltage of the MOSFET V_{gs}, and *CH3* (bottom, pink) is for the control signal for the switch output from the MCU.

The V_{gs} rises very slowly as shown in Fig. 5(a) before using enhanced switch. It has great influence on the conversion efficiency of the PFM regulator while the V_{solar} remains in the low level most of the time. By adding a diode $D1$ to the circuit of the switch in Fig. 3(d), it reduces the response time of the V_{gs}, as shown in Fig. 5(b), which improves the controllability to the solar panel V_{solar} and hence increases the conversion efficiency of the PFM regulator.

Power Path Switch for Supercapacitor Array Fig. 6 shows the charge curve comparison between using power path switch and the N-MOSFET switch. The red line is the charge curve for the N-MOSFET switch, and the blue line for the power path switch. When using the N-MOSFET switch, V_{gs} decreases as the voltage of the supercapacitor increases during charge time, and then the N-MOSFET turns off when the V_{gs} is lower than V_{th}. It occurs when the supercapacitor is charged to 1.3V. By replacing the N-MOSFET switch with the power path switch, the charge curve appears efficient even when the supercapacitor voltage exceeds 1.3V.

5.2.2 I-V Curve Tracing

Fig. 7 shows the voltage, current, and power curves during I-V curve tracing. The DAC outputs a linear incremental voltage signal to the gate of an N-MOSFET during I-V tracing, which controls the load of the solar panel indirectly. Since the N-MOSFET behaves linearly just in a short range of V_{gs}, the curve appears only in a short part of the captured data. Fig. 8 shows the I-V curve that is transformed by the result of I-V tracing in Fig. 7. The black square shows the I-V curve of the solar panel, and the green triangle shows the P-V curve in the figure.

5.2.3 Charging Comparison

Fig. 9(a) shows the measured times of charging the 25F, 2.7V supercapacitor to 2.0V. Linear charging [2, 3] takes the longest time,

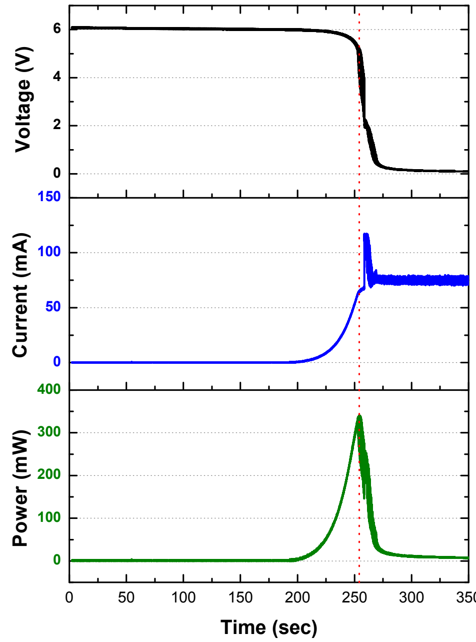


Figure 7: Solar panel I-V tracing performed by I-V tracer.

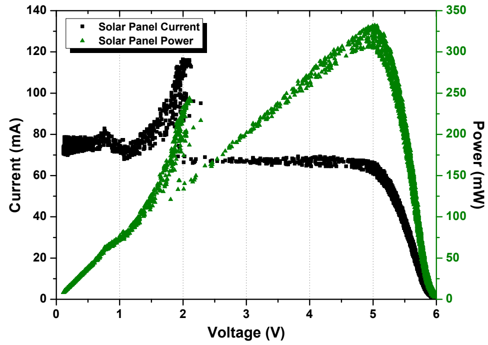
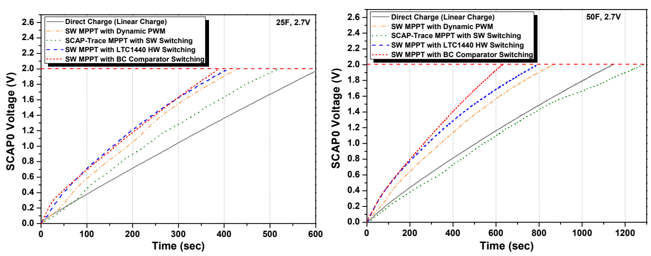


Figure 8: Solar panel I-V curve measured by I-V tracer.



(a) (b)

Figure 9: Comparison of voltage over time for charging supercapacitors: (a) 25F (b) 50F.

610 seconds to reach 2.0V. Bound-control (this work) and LTC1440 (used by [1,5]) reach 2.0V in 389 and 410 seconds, respectively, as their principles of operation are similar. They charge the supercapacitor to 2.0V nearly 56% faster than linear charging. Fig. 9(b) shows the experimental result of charging the 50F, 2.7V supercapacitor to 2.0V. This time, the bound-control MPPT reach 2.0*V* in 631 seconds, which is 25% faster than the LTC1440 MPPT (791s) and 81% faster than linear charging (1145s). Fig. 10 and Table 2 summarize the charging time for each MPPT approach. The bound-control circuit appears to be the most efficient MPPT approach in DuraCap to charge the supercapacitor.

6. CONCLUSIONS

This paper presents a micro-solar energy harvesting system named

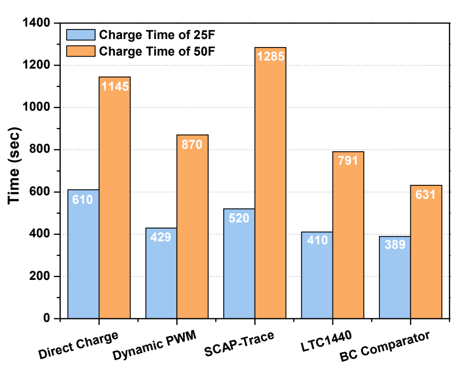


Figure 10: Comparison of charging times for 25F and 50F supercapacitors by different charging methods.

Table 2: 25F vs. 50F charge time comparison

Supercapacitor	Linear Charge	Dynamic PWM	Supercapacitor Tracing	LTC1440 MPPT	Bound-Control MPPT
25F, *2.0V*	610*s*	429*s*	520*s*	410*s*	389*s*
50F, *2.0V*	1145*s*	870*s*	1285*s*	791*s*	631*s*

DuraCap. The use of supercapacitors instead of batteries is expected to enable DuraCap to extend the lifetime of the system from a few years to tens of years. DuraCap further overcomes several limitations with previous designs. First, dedicating a supercapacitor to booting enables DuraCap to deliver stable power at a sufficiently high voltage quickly, so that the system is able to recover rapidly from total exhaustion of stored energy. The system charges the supercapacitor by using a PFM regulator that significantly increases the conversion efficiency without mistaking an uncharged supercapacitor for a short circuit, as feedback regulators do. Our bound-control PFM regulator controller for MPPT also allows the system to maintain the maximum power level that can be transferred from the solar panel. Most importantly, unlike other micro-solar MPPT systems that hardwire the I-V table, DuraCap is self-configuring using its built-in I-V tracer. This feature enables DuraCap to automatically match the characteristics of different solar panels or the same panel over its aging process. DuraCap itself runs on harvested power with minimal overhead, thanks to not only an ultra-low-power microcontroller, but also our own low-voltage control circuitry in the form of an enhanced switch for the PFM regulator and a power path switch for the supercapacitor array.

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