Techniques for Maximizing Efficiency of Solar Energy Harvesting Systems (Invited Paper)

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Abstract

Energy harvesting capabilities enable totally untethered operation of mobile and ubiquitous systems for extended periods of time without requiring battery replacement. This paper examines technical issues with solar energy harvesting. First, maximum power point tracking (MPPT) techniques are compared in terms of solar cell model, tracking source, and controller style. For energy harvesting in conjunction with energy storage, this paper compares batteries and supercapacitors, and discusses trade-offs between complexity of charging circuitry and efficiency. Recent techniques for handling cold booting are also examined in terms of both hardware and software solutions. This paper assumes mainly small-scale photovoltaic sources, although many techniques apply to other sources as well. Together, the increase efficiency is expected to enable more compact, lower cost energy harvesters to bring longer, more stable operation to the systems.

Keywords: Maximum power point tracking, energy harvesting, solar panel, photovoltaic cell, supercapacitor, ultracapacitor, battery, DC-DC converter.

1 INTRODUCTION

One main limitation with many mobile and ubiquitous systems is the battery life. Battery replacement can be inconvenient, while larger batteries may add to the bulk and cost. One possible solution being considered is to harvest energy from various sources. Plenty of ambient energy is available, and many renewable energy sources, such as solar radiation, wind power, thermal differential, vibration, hydroelectric, and fuel cell have been gaining attention.

Among various ambient energy sources, solar radiation energy is the most popular for outdoor applications, even though it is dependent on the meteorological conditions. It has higher power density than other renewable energy sources, and this allows a sensor node to collect sufficient energy in a small form factor. Even when used indoors, ambient room lighting has been shown to be powerful enough to drive peripherals such as ultra low-power displays and even wireless networking cards, not just calculators.

The design goals of an energy harvesting system for mobile and ubiquitous computing systems include high conversion efficiency, long operating life, low overhead, low cost, and small size. An important problem that must therefore be addressed is that of maximum power point tracking (MPPT). The maximum power point (MPP) is the load at which the transferred power ($= I \times V$) is maximized for a given level of ambient power. By tracking the MPP, the system can harvest more energy using a smaller panel than one that uses a larger panel but does not perform MPPT. However, it is important to minimize overhead for MPPT, because the overhead may more than offset the gain. The idea of MPPT is not only limited to solar panels but also applies to wind and waterturbine.

A key component associated with energy harvesting is energy storage. Although not strictly required in all systems, energy storage is commonly used to sustain long periods of operation without steady supply of ambient power. By default, rechargeable batteries are used, but more recently, supercapacitors are used either in addition to or instead of batteries for reasons of many more recharge cycles and higher power density. However, unlike batteries, where the voltage remains relatively even over most of the battery's remaining charge levels, a capacitor's voltage scales linearly with the remaining energy. This means additional circuitry is required to make the energy usable.

Another related issue with energy harvesting systems with storage is that of cold booting. This is a condition when the system starts running from zero stored energy. If the system starts booting up as soon as it has harvested enough energy, it is likely to drain the energy shortly after booting, forcing the system to reset and repeat the cycle of futile attempts to boot up. The better solution is to hold off booting until sufficient energy has been harvested, although being too conservative translates into increased latency.

This paper discusses the problems of the three aspects of energy harvesting: MPPT, energy storage, and cold booting. We evaluate these techniques for their ability to achieve a balance between high conversion efficiency, low hardware and software complexity, and long operational life time.

2 MAXIMUM POWER POINT TRACKING

One important issue in maximizing the efficiency of an energy harvesting system is to maximize the amount of energy transferred from the source, i.e., operating at the MPP. The problem is that the MPP is a function of the ambient power level, and it is achieved by controlling the load. This section first provide a background on energy sources, specifically solar panels, in terms of an equivalent circuit model. Next, it presents approaches to MPPT, followed by a discussion of implementation issues.

Table 1: Feature comparison of recent energy harvesting systems

Work	Sources	MPPT	Storage	Coldboot	Controller	Goal
PUMA [1]	solar, wind	power routing	Li-ion	n/a	shared	utility
AmbiMax [2]	solar, wind	sensor	1 sc/src	n/a	V comp	MPPT
Everlast [3]	solar	V_{oc} table lookup	supercap	feed fw	shared MCU	long life
DuraCap [4]	solar	I-V sweep	3 supercaps	boot cap	dedic MCU	life, coldboot
Brunelli et al [5]	solar	pilot cell	sc+batt	n/a	analog	MPPT
Heliomote [6]	solar	n/a	NiMH	n/a	shared MCU	solar
Prometheus [7]	solar	n/a	sc+batt	n/a	shared MCU	minimize batt
Twin-Star [8]	solar	n/a	supercap	Schmitt trigger	companion node	cold boot
Fleck [9]	solar	n/a	NiMH or sc	n/a	shared	long life
Solar Biscuit [10]	solar	n/a	supercap	bootstrap mode	shared	batteryless
ZebraNet [11]	solar	comparator	Li-ion	n/a	analog	long RF dist

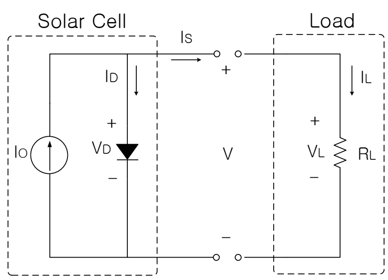

Figure 1: Equivalent Circuit Model of Solar Cell.

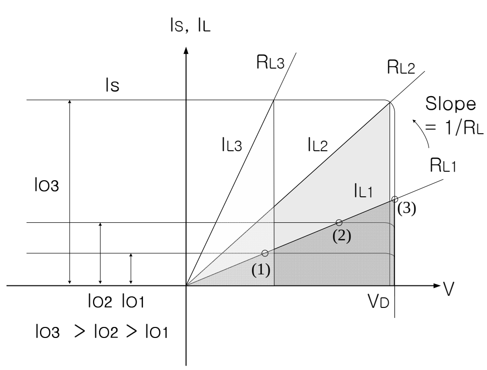

Figure 2: I-V Curve and Load lines of a Solar Cell.

2.1 Solar Cell Modeling

A solar panel consists of a matrix of solar cells, also known as photovoltaic (PV) cells. This section explains how a solar panel works in terms of a circuit model. Fig. 1 shows the equivalent circuit model of a solar cell. It can be described as one ideal current source and a voltage limiter, as shown in Fig. 1, where I_O is proportional to the sunlight intensity. Therefore, one of the most important issues for a solar cell is how to efficiently deliver as much power to the load (represented by R_L) as possible for a given I_O, as determined by a given level of sunlight intensity.

For illustration, assume that I_O increases gradually. When I_O is small, most I_O will flow to R_L, because the diode does not turn on before reaching 0.7V. As I_O increases, V_L will eventually approach 0.7V, and the diode turns on. As a result, any additional increase of I_O will result in current flowing to the diode instead of the load. Thus, at high I_O, V_L is approximately 0.7V and I_L is saturated at $0.7/R_L$. Therefore, we can invoke,

$$I_S = I_O - I_D \tag{1}$$

$$I_L = V/R_L \tag{2}$$

The solution for $I_S = I_L$ and V can be found by plotting I_S and I_L separately vs. V as shown in Fig. 2. By graphical load-line analysis, the solution for $I_S = I_L$ and V changes from (1) to (2) and (3) as I_O increases. After approaching the point (3), any further increment in I_O will not affect the power conversion efficiency. At this point, one can increase the power conversion efficiency only by lowering R_L, because the slope of the load line is inversely proportional to R_L. In detail, the shaded area of Fig. 2 is equal to harvested power that is transferred to the load. Comparing the three load-resistor values R_{L1}, R_{L2}, and R_{L3}, R_{L2} results in the maximum power conversion when the "diode" is just turned on. This analysis result shows that adjusting the slope of the load line is the pivotal parameter for transferring the maximum power from the solar cell to the load. The saturation voltage V_D can be increased beyond 0.7V by the series and parallel composition of the solar cells. This means that this analysis can be applied to a solar panel.

2.2 MPPT Approaches

The purpose of maximum power point tracking (MPPT) is to track the supply condition and determine the corresponding load that maximizes the transferred power. The harvesting efficiency can be controlled by adjusting the slope of the load line to near the peak of the I-V curve as mentioned in Section 2.1. However, MPPT is not always performed in *small-scale* energy harvesting systems [6–10], also called *micro-solar* systems, for several reasons. Traditional MPPT mechanisms may incur nontrivial overhead, sometimes even higher than the amount of power harvested by the small solar panel, and thus it may not be worth performing. Second, one can always *over-engineer* the system by putting in a larger panel than necessary, so that it still outputs sufficient power even when operating at very inefficient levels. However, for mobile and ubiquitous systems that are cost-sensitive or size-constrained, it is important to use the smallest panel possible by maximizing its efficiency in order to achieve sustainable operation.

Approaches to micro-solar MPPT, therefore, must consider the net amount of power that can be transferred, after the MPPT overhead has been subtracted. One common approach is to sacrifice MPPT optimality for significantly reduced overhead. That is, by harvesting within, say, 5-10% from the MPP, one may cut down on the MPPT overhead significantly, which may result in much higher net power. One way to classify MPPT approaches is consumption side vs. supply side. Consumption side is represented by load matching, while supply side is further divided into sensor-driven and perturbation-based MPPT.

2.2.1 Load Matching

A consumption-side micro-solar MPPT approach is called *load matching*, which means to adjust the load directly to maximize the utility of power when available. The load can be adjusted by duty cycling or dynamic power management (DPM), among many techniques published in the low-power literature. One reason for maximizing power utility is to minimize power loss due to conversion and energy loss due to storage [1, 12], although one can always store the excess power as yet another form of load.

Actually, load matching is a special case of *load following*, where the duty cycling [13] or DPM [8] tracks the level of available power (e.g., based on a light sensor) without necessarily tracking the MPP (i.e., transferred power). Because load following does not necessarily track the MPP, it can actually lead to system failure if there is no energy storage, because overloading the solar panel will result in lower transferred power than the peak load. Another consideration is that, both load matching and load following tend to be application specific.

2.2.2 Sensor-driven MPPT

With sensor-driven MPPT, a sensor is used to measure the intensity of the ambient power, which is the primary parameter that determines the MPP. For instance, the MPP for a solar panel is primarily determined by the light intensity, and the MPP for a wind generator is primarily determined by the rotational speed of the fan. Then, the sensor value can then be used to determine the load that will result in the MPP. The use of a sensor does not require perturbation to the energy harvesting source and enables very simple circuitry to be built, such as the case with AmbiMax [2]. In fact, AmbiMax can also take a rotational speed sensor for a wind generator. However, a sensor itself consumes power, even if it is a trivial amount. One alternative that addresses this problem is to use a *pilot cell*, which is a miniature solar panel that outputs its harvested power instead of consuming power [5]. A small pilot cell can be made in about the same size as a photo sensor.

In both cases, however, under partial shading conditions, either the photo sensor or the pilot cell may fail to output a representative value for the solar panel's exposure to solar power. A related problem is aging and other forms of deterioration, where even without partial shading, the photo sensor or the pilot cell's output is no longer a good indicator of the MPP. In the latter cases, the energy harvesting system would need to be re-calibrated.

2.2.3 Perturbation-based MPPT

Perturbation-based MPPT approaches do not rely on sensors to measure the ambient power level in order to derive the MPP; instead, they test the generator itself to determine the MPP. Such MPPT approaches include open circuit voltage, short circuit current, hill climbing, and I-V curve sweeping.

Open circuit voltage (V_{oc}) and short circuit voltage (I_{sc}) approaches use either V_{oc} or I_{sc} to determine the ambient power level [14]. In a sense, this can be viewed as using the entire solar panel as a sensor. However, the price to pay is that it requires the load to be disconnected momentarily while the V_{oc} or I_{sc} is measured. One may approximate the V_{mp} or I_{mp} as a linear function of V_{oc} or I_{sc}, respectively:

$$V_{mp} = k_1 V_{oc} \tag{3}$$

$$I_{mp} = k_2 I_{sc} \tag{4}$$

where k_1, k_2 are proportional constants.

Once k_1 and k_2 are known, I_{sc} can be simply measured by shorting the solar cell using periodic switching operation, and V_{oc} also can be measured periodically by momentarily shutting down the power converter. To handle the temporary loss of power while measuring V_{oc} or I_{sc}, some circuitry such as a capacitor is required to keep the rest of the system on. The accuracy of V_{mp} and I_{mp} depends on the constants k_1, k_2.

A more accurate method is called hill-climbing, where perturbing the duty ratio of the power converter perturbs the solar panel's current and consequently perturbs the solar panel's voltage [15]. At the P-V curve, if the power is increased, the subsequent perturbation must be generated until it reaches the MPP. In contrast, if the power is decreased, the subsequent perturbation should be reversed. This process is repeated until the MPP is reached. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation size slows down the convergence speed of MPPT. In this sense, even though hill-climbing is more accurate, it has the drawback that the convergence speed is unstable depending on the perturbation step size. Hill-climbing tracks two points in order to find the MPP, and thus it consumes more power than V_{oc} or I_{sc} method.

I-V curve sweeping is an even more precise MPPT approach, which measures the I-V characteristic of the solar panel by varying a test load. Note that all other approaches also need to rely on some characterization of the solar panel, also done by sweeping the I-V curve, except they are done before deployment. The advantages to doing I-V curve sweeping at runtime are that (1) it tracks the exact characteristics of the solar panel over time, even as it ages or becomes dusty, (2) the same MPPT logic can work with a wide range of replacement solar panels automatically, without requiring the user to manually characterize each one and updating the control parameters. As with other perturbation-based MPPT techniques, I-V curve sweeping at runtime also requires the system to be disconnected from the solar panel momentarily. It may incur slightly more cost, but in practice the cost is only slightly higher than other simpler perturbation-based MPPT approaches.

2.3 Implementation Issues

MPPT approaches described above can have multiple implementations. The MPPT controller may be shared with the main MCU of the system or autonomous (dedicated). Among dedicated controllers, one has the option of using either analog or MCU control.

2.3.1 Shared vs. Dedicated Control

Shared MCU is used for charging control and power management without MPPT [6,7,9,10] and with MPPT [1,3]. Such a controller can potentially exploit knowledge about the application to manage not only power consumption but also harvesting more effectively. However, the application-specific nature also means the work is less usable over other power consumers. Among these systems, as long as the MPPT approach does not rely on load matching or load following (Section 2.2.1) [1, 10, 13], then it can also be implemented using an autonomous controller.

An autonomous controller enables the entire energy harvesting subsystem with MPPT to be made into a self-contained unit, making it modular and reusable over a wide variety of systems [2, 4, 5]. Some such systems can directly replace batteries by outputting the same voltage level [4] without modification to the power consumer.

2.3.2 Analog vs. Digital Control

Sensor-driven supply-side MPPT approaches (Section 2.2.2) have the option of using analog control to create a very simple MPPT circuitry [2, 5] without involving an MCU. This is because the control signal is approximated as a linear function of the sensor value and therefore can be scaled by a simple resistor. These analog components consume very low power and are capable of tracking the MPP continuously, making them effective for deployment scenarios where the supply condition changes rapidly. However, one common fallacy is to assume that analog control to be always more energy efficient. This is because digital control, in particular MCUs, can be power managed by duty cycling. Even though the on-power of an MCU may be higher, it can be off for much longer due to the low duty cycling requirement, and thus the total energy may be lower.

Software implementation is most general and can be applied to both sensor-driven and perturbation approaches. This is because software can model arbitrary I-V curves in terms of a subroutine or a lookup table [1,3]. By default, the characterization is done before deployment and stored in the firmware memory of the energy harvester. As the solar panel ages or otherwise changes characteristics over time, however, the software model may no longer correctly characterize the panel. In that case, the firmware should be updated over time, but how to re-characterize the solar panel remains a problem, unless the harvester performs I-V curve sweeping by itself [4].

Software control can be used in conjunction with autonomous analog control for evolvable characterization. The software can re-characterize the panel by I-V curve sweeping over time, and then it can update programmable potentiometers that are used as analog parameters to the MPPT control. By using nonvolatile programmable potentiometers, the MPPT circuitry can work autonomously without an MCU.

3 HARVESTING WITH ENERGY STORAGE

3.1 Storage Types

Batteries are the primary type of power source for mobile and many ubiquitous systems. Among rechargeable batteries, Li-ion and Li-polymer batteries have the highest energy density and high charge-to-discharge efficiency. Charging of a lithium type battery is more complicated and is usually handled by a charging IC. Several works cited this reason and chose nickel metal hydride (NiMH) batteries instead. NiMH is one of the most popular types of energy storage for its relatively high energy density and relatively simple charging method, i.e., trickle charging. Nickel-Cadmium (NiCd) batteries have the advantage of higher discharge rates and can tolerate deeper discharge cycles than lithium batteries. However, in practice, they can suffer from a memory effect, or an apparent loss of capacity if it is recharged before fully discharged. Rechargeable batteries also have a limited number of recharge cycles on the order of 1000.

In recent years, *supercapacitors*, also known as *ultracapacitors* or *electrochemical double layer capacitors* (EDLCs), have been proposed as an alternative to rechargeable batteries for a range of applications [16]. They have capacitance

Table 2: Comparison between Batteries and Supercapacitors

	Battery	Supercapacitor
Recharge Cycle Life Time	$< 10^3$ cycles	$> 10^6$ cycles
Self-discharge Rate	5%	30%
Voltage	3.7V-4.2V	0V-2.7V
Energy Density (Wh/kg)	High (20-150)	Low (0.8-10)
Power Density (W/kg)	Low (50-300)	High (500-400)
Charging time	sec $\sim$ min	hour
Discharging time	$<$ a few min	0.3$\sim$3 hours
Charging Circuit	complicated	simple

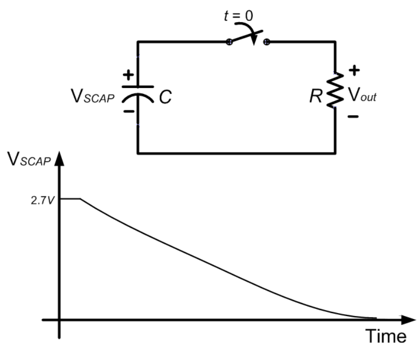

Figure 3: Discharge curve of a Supercapacitor.

values on the order of tens to hundreds of farads and are now approaching the energy density of batteries within an order of magnitude. The properties are their power density, low equivalent series resistance (ESR), and lower leakage current than electrolytic [17]. Table 2 shows a comparison between batteries and supercapacitors. Although its capacity is still much smaller than other types of batteries, a supercapacitor stores enough energy to power many mobile and ubiquitous systems. In particular, its relatively high maximum recharging cycle life time allows it to be used for long-lifetime applications.

3.2 Storage Approaches

Virtually all energy harvesting systems incorporate one or more energy storage devices. Solar panels were added to replenish batteries for extended operations [1, 6, 9, 11]. However, limitations with batteries prompted researchers to consider hybrid or batteryless schemes.

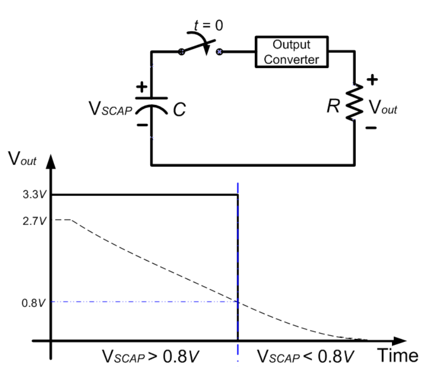

Figure 4: Constant V_{out} by buck converter.

One purpose of hybrid supercapacitor-battery schemes is to avoid discharging the battery by prioritizing the charging and discharging to the supercapacitor [7], and the battery is used as an emergency backup. However, the hybrid concept is a distinct idea from MPPT. In the case of Prometheus, its diode-based charging circuitry without any DC-DC converters means it harvests power only during the brightest hours of the day and can waste energy, as discussed in Section 3.3.1.

Several batteryless schemes have been proposed, where the battery is replaced entirely by one or more supercapacitors. Solar Biscuit [10] and Twin-Star [8] are designed to be batteryless as the primary goal, though they do not perform MPPT. Fleck [9] was originally designed to work with a battery, but it was also tested with a supercapacitor without considering its specific characteristics, making its operation less effective. Among those that perform MPPT, circuits that take into the account of supercapacitor characteristics are designed for charging and discharging [2–5], which are discussed next.

3.3 Charging and Discharging Schemes

Battery discharging is the same whether energy harvesting is used or not. On the other hand, the output voltage of a supercapacitor is linearly proportional to the stored charge, and it definitely requires a regulator (DC-DC converter) to output a stable voltage. Because a significant amount of energy is still usable when a supercapacitor's voltage drops below a usable threshold, a buck-boost regulator is commonly used when supplying power to the consumer. Charging circuits, on the other hand, vary tremendously even among a given type of energy storage. It is possible to use standard circuitry such as charging IC (e.g., for Li-ion batteries), but it may result in energy waste if not careful. Depending on which component is set between solar panel and the energy storage, the charging structure of solar harvesting systems can be classified into three categories: diode only, buck/boost converter, and pulse frequency modulation (PFM) regulator. The rest of this subsection is devoted to charging issues.

3.3.1 Diode-Only Charger

With a diode-only charger, the solar panel is connected to its battery or supercapacitor through a diode. The purpose of the diode is to prevent reverse current during low-light conditions [6, 7, 10], and the diode may be implicit as part of the panel [8]. However, a diode does not perform MPPT. Moreover, it is not efficient, because a diode takes a 0.7V drop, which effectively raises the charging threshold by 0.7V. To put it in perspective, a 300F supercapacitor with a 0.7V higher charging threshold effectively discards 2100 mAh of charge every ten hours. That is about the capacity of a conventional AA battery.

3.3.2 Boost Converter

One solution to the diode waste problem in charging from an energy harvesting source is to use a boost regulator, which raises the voltage to a usable level. For example, in AmbiMax [2], the diode is replaced with a PWM boost converter, which also serves the purpose of a diode to block the reverse current flow from the supercapacitor to the ambient power source, but without the overhead of 0.7V drop. Fig. 3 shows the linearity of the supercapacitor's discharge, while Fig. 4 shows how a DC/DC converter can turn it into usable voltage at 3.3V. However, one must be careful with just putting a regulator in directly. This is because a supercapacitor appears as a short circuit, or infinite load, when it is near depletion. In fact, energy harvesting systems that rely on feedback regulators to charge supercapacitors (e.g., AmbiMax [2]) will suffer from this problem: the apparent infinite load can cause the regulator to reduce the current and charge the supercapacitor very slowly when it starts from empty. Adding a current limiter in series can solve this problem, but the MPP mechanism may need to be re-calibrated.

3.3.3 PFM Regulator

To address the problem with feedback regulators, a PFM regulator can be used to meet the requirement of efficient charging of a supercapacitor from a high impedance power source. The PFM regulator has the advantages of both the switching capacitor regulator and the buck converter to prevent shorting the input and output. It also solves the problem of inefficiently charging a supercapacitor in its depletion state [3].

4 COLD BOOTING

Cold booting, also known as the *zero-energy boot-strap* problem, is one where the system starts up from no stored energy in an energy harvesting system. A system can enter this state after having been deprived of sunlight for an extended period of time and more sunlight is just becoming available. This is problematic, because if the system starts booting as soon as the harvested power exceeds the usable threshold, it is likely to fail if the harvested power does not increase monotonically. The MCU may boot successfully, but any surge due to RF activities can quickly cause any just harvested stored power to be depleted quickly, too, causing the entire system to fail. Such a system is likely to repeat the futile attempt to boot up until sufficient sunlight is available.

Cold booting has not been seen as a problem, either because many systems have been *over-designed* – with a larger solar panel than necessary, or because the systems are inefficient due to high threshold (Section 3.3.1), i.e., substantial sunlight is needed before the system becomes operational. Some recent works start addressing the problem [4,8,10], and this section discusses their trade-offs. The solutions to cold booting be classified into software control, inhibited start by Schmitt trigger, and bootstrap supercapacitor.

4.1 Software Control

The software solution to cold booting is to have the MCU check the charge level of the energy storage before deciding whether to wait or run. An example of such a system is Solar Biscuit [10], where the node remains in *bootstrap mode* until it has harvested enough energy, at which time it enters *ordinary mode*. This is a simple software solution that increases stability of the network, but the solution is specific to the application.

4.2 Inhibited Start by Schmitt Trigger

A simple hardware solution is to use a Schmitt trigger to inhibit starting the system until the energy storage has accumulated sufficient charge. A Schmitt trigger is a dual-threshold device with two states: it outputs a low value until the input exceeds a high threshold, in which case it outputs a high value. The output remains high even if the input drops below the high threshold, and the output switches to the low value only after the input drops below the low threshold. By feeding the voltage that is proportional to the main energy storage to the Schmitt trigger, the output of the Schmitt trigger can be used as input to a $\overline{\text{SHDN}}$ (shutdown, active-low) signal of the main regulator to inhibit the start until the energy storage has sufficiently high voltage (and therefore charge level).

One example of a system that incorporates this solution is the Twin-Star [8]. However, one issue it must address is how to power the Schmitt trigger itself, and Twin-Star's solution is to use a smaller *boot panel*, somewhat analogous to the pilot cell [5] plus another capacitor. Depending on the size of the panel, the extra panel may add to the cost of the system. Twin-Star does not perform MPPT. Another problem is that because the Schmitt trigger's input is powered by both the output of the regulator and a separate capacitor, the Schmitt trigger could still remain on even though the main energy storage (supercapacitor) is empty.

4.3 Bootstrap Supercapacitor

Another hardware solution that addresses the cold booting problem is to include a bootstrap supercapacitor, or bootcap for short [4]. During cold booting, the energy harvester does not supply power to the power consumer but charges the bootcap, which is of a smaller capacity relative to the primary energy storage. It can be charged up to a sufficiently high voltage quickly, and then it starts supplying power to the target system as soon as possible. While the system draws power from the bootcap, the solar panel charges the primary energy storage, which can be a rechargeable battery or one or more supercapacitors. In the case of DuraCap, two reservoir supercapacitors are used to enable I-V curve tracing.

When the bootcap is exhausted, the system switches to drawing power from the reservoir supercapacitors. If all stored energy is exhausted, then it runs on solar power alone until it cannot run any more. At any time, when more solar energy is available for charging, the bootcap is always charged first to reach the sufficiently high voltage. Unlike Twin-Star, which requires some power to control the Schmitt trigger, DuraCap uses nonvolatile digital potentiometers to set the bounding voltages for the comparators after I-V curve tracing. Thus, it can also perform MPPT autonomously.

5 CONCLUSIONS

Energy harvesting is an increasingly important problem in mobile and ubiquitous systems. Until now, inefficient aspects in previous energy harvesting systems have been masked by over-design, e.g., using a larger solar panel than necessary. However, as energy harvesting becomes a mandatory feature in ubiquitous systems, cost and size constraints will force designers to increase their efficiency level. This paper examines in detail the pitfalls in existing designs and suggests solutions for achieving low-overhead, high conversion efficiency, and durable power that extends the life time from several months to tens of years. MPPT must be performed to harvest the maximum power from the source, but at the same time the overhead must be kept low in order to maximize the net gain. We discussed issues in MPPT controller and charging circuitry designs that lead to energy waste. For instance, analog control or diodes, although simple, may need to be replaced with digital control or boost regulators in order to increase harvesting efficiency; another instance was the 0.7V drop in a seemingly innocuous diode in a charging circuit, whose small energy waste can add up to a whole battery's worth of energy in less than half a day. Finally, we also discussed cold booting as an important problem, as it affects how quickly a system can start sustainable operation. Together, these approaches and charging techniques, with a consideration for controller style and cold booting, ensure that the system is able to not only run smoothly on harvested power but also recover rapidly from total exhaustion of stored energy.

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