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Maximum power tracking in solar cell arrays using time-based reconfiguration

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ABSTRACT

Directly harnessed solar power is an attractive primary energy source for integration into fully wire-free, self-sufficient, portable electronic devices. Maximum power (MPP) tracking of photovoltaic (PV) cells is an essential part of PV energy harvesting and several methods are available to track MPP efficiently. With more than one cell, power-balancing is also a significant concern and global MPP tracking, parallel connection of PV cells, and active array reconfiguration are all techniques designed to address this issue. This work shrinks array reconfiguration from two-dimensional arrays of PV cells to a single string of PV cells, which are particularly relevant to portable systems. Each string element has individual MPP tracking and power balancing at low circuit complexity using a modular, time-domain array-reconfiguration (TDAR) approach. Both, a discrete control loop that demonstrates the concept and a 150 μW microchip that implements TDAR for three PV cells were developed. The energy harvesting efficiency of the TDAR approach is more than 80% improved compared to static (non-reconfigurable) strings of PV cells. While other array reconfiguration approaches can offer comparable improvements in efficiency, the reduced complexity of the TDAR approach makes it the only scalable approach that can be practically applied to array reconfiguration in portable systems.

1. Introduction

An attractive method for powering electronic portable devices is harnessing solar energy using photovoltaic (PV) cells built into appropriate energy harvesting systems. Most practical single-junction PV cells have an operating voltage between 0.3 V and 0.6 V which is lower than the typical 1 V operating voltage of contemporary microelectronics [1]. Thus, making an effective solar system using PV cells requires connecting individual PV cells in series to generate a sum (series) voltage sufficient to power the corresponding electronic load, be it a small (self-contained micro-scale) system or a much larger system that feeds into a centralized power grid. Once connected in series, these series connections (strings) of PV cells can then be connected in parallel with similar PV strings to generate the desired current for the system as exemplified by Shen et al. in [2]. Mismatches and non-idealities in component PV cells, both static and dynamic, can cause losses in power delivered by the system, thus compromising system efficiency and usefulness [3,4]. These dynamic changes are especially prevalent in portable or micro-scale systems (as compared to fixed, large-scale systems that connect to a centralized power grid). A variety of approaches has been developed to address both static and dynamic variations in PV cell and array operation. This work presents a novel approach to PV cell and array management that not only captures the optimal operating point (MPP) from each cell but also accommodates dynamic changes in the operating environment by reconfiguring the array to optimize performance while substantially reducing the additional hardware and software that is typically required for such reconfiguration.

2. Theory & background

At the micro-scale, in portable devices powered by solar energy harvesting systems, PV cells in an array are vulnerable not only to the fixed fabrication mismatches found in large-scale solar energy systems but are also prone to dynamic variations caused by broad fluctuations in environmental conditions (shading, soiling, etc.). For example, PV cells may be made of a flexible or other lightweight material, such as amorphous silicon, organic small-molecule, or polymer [5] to meet footprint and weight considerations in portable systems. Bending and other movement in such cells can cause differential orientation and conductive mismatches during operation. Such non-standard materials or irregular topologies of these materials may then exhibit high batch mismatch during fabrication or degradation, which can lead to shorter lifetimes when corresponding PV cell management approaches are not

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designed for such portable systems. Once deployed into a field environment, portable microsystems are also more vulnerable to soiling as well as to sudden and significant changes in shading conditions during real-time operation, much more so than their fixed location, high density power grid counterparts. Despite the larger fluctuations in operating point inherent to portable operation, portable PV systems can borrow extensively from large-scale PV management concepts as shown in systems designed and demonstrated in [6,7]. Ultimately, both dynamic and static sources of variation in PV cell operation impact the ability of the cell to produce the optimal (maximum) power for each PV cell. Thus, the challenge of designing these systems is both to locate and enable each cell to operate at its MPP.

2.1. MPP tracking (MPPT)

MPPT is the process of searching for and locating the MPP of each PV cell in an array of such cells. MPPT is an area of considerable research in PV cell management. Esram and Chapman have an excellent review of MPPT techniques [8]. In the most common approach, the MPP can be found by changing the duty cycle of the PV cell in the direction of increasing power until the highest (maximum) power is reached (‘Hill climbing’). In contrast, “perturb and observe” algorithms directly change the voltage or current in a PV cell to seek the MPP. A comparison of these two methods is found in the paper by Fangrui Liu et al. [9]. P&O (perturb and observe) algorithms provide faster performance and better regulated output voltages, but Hill climbing strategies, because they are much simpler and easier to implement, are well suited to portable microsystems. Another approach to MPP tracking extracts the first derivative of the power–voltage curve dP/dV and then seeks to maintain this derivative at 0, which corresponds to the maximum of the power curve [10]. Other digital methods such as fuzzy logic control [11,12], derivative feedback [13], and fractional voltage or current [14] attempt to minimize the parameters that must be extracted from PV cells by using a-priori knowledge of the PV system and its operating point [15]. All digital methods of MPPT are subject to a large amount of (power and real-estate) overhead, thus limiting their application to portable microsystems.

In portable systems, MPPT must be accomplished primarily in hardware with little if any software intervention in order to meet stringent size, weight, and power requirements. Analog-domain implementations of MPPT are particularly amenable to portable systems because they are capable of significant computing at lower power than many corresponding digital systems. Ripple correlation approaches to MPPT [16–18] are well matched to analog-domain implementations of MPPT. Because ripple correlation allows only small perturbations around the MPP, the MPP can be found asymptotically at maximum speed [8].

2.2. Array reconfiguration

Array reconfiguration is the method by which PV cells in a system are enabled to operate at or near their individual MPPs. When PV cells are applied to solar energy harvesting applications, multiple cells are invariably connected in series (strings) for higher voltage output and these strings are subsequently placed in parallel to improve current output. Non-uniformity in the power contributed by constituent PV cells due to dynamic or static variations in operation, can cause the current–voltage relation of the string to be complex with multiple local maxima occurring within the power–voltage curve [19]. These unequal contributions from PV cells have, to date, been addressed in three major ways: (a) ignore local maxima and maintain PV arrays at their (global) MPPs including blocking or bypassing cells that are drawing power rather than supplying it to the overall array; (b) connect cells in parallel to avoid multiple maxima in characteristics; and (c) physically reconfigure cell connections to correct for non-uniformity [8].

(a) *Global MPP tracking* [16]: ignores the individual MPPs of individual PV cells and instead tracks only the current and voltage of an entire array. While achieving more power output than in the absence of MPP tracking, Global MPP tracking does not guarantee maximum power extraction from any given array of PV cells, because when an array is addressed using global MPP tracking, partially illuminated PV cells are bypassed by reverse biasing them using diodes. Blocking diodes are also connected in series with an entire string of cells, preventing one string from loading down another during operation. As passive circuit elements, these diodes, although they prevent substantial power drains on the system, nevertheless consume power that could, if properly captured, be used to charge the battery in a portable device.

(b) *Parallel connections* of PV cells [2] are another way to address non-uniformities in PV cell arrays. Cells connected in parallel match better than series strings under dynamic environment changes such as those caused by partial shading [19,2], because MPP voltage fluctuates less with these changes than MPP current. Predominantly parallel connections among PV cells avoid altogether current-balancing problems inherent to series connections among cells (strings) and also keep system current–voltage characteristics close to that of a single component PV cell. However, the more parallel the array for a given number of PV cells, the less the output voltage. Reduced output voltage from an energy harvesting source translates into lower overall efficiency in the energy harvesting system because of boost converter limitations [20].

(c) *Physical Array reconfiguration* [4,20–23] changes connections among PV cells in an array to optimize the power produced by that array. Array reconfiguration minimizes the constraints on voltage boost electronics by keeping array voltage high while also actively current-balancing PV cells. These two desirable characteristics (high voltage, balanced current) are achieved simultaneously using dynamic adjustments to the interconnections between PV cells. Common approaches to array reconfiguration use a static array and an adaptive bank of PV cells that are connected to a switching matrix. Since the major features of such systems are the switching matrix for the PV cells and the power-tracking electronics for each switched element, research in this area emphasizes the reduction of complexity in the switching matrix and power-sensing electronics [24,25] and also quick reconfiguration response using optimized tracking algorithms [22,26]. Array reconfiguration requires substantial overhead, which while justifiable for large arrays of PV cells, is often prohibitive for portable devices and microsystems.

2.3. Novel approach

Time Domain Array Reconfiguration (TDAR) *System*: The system described herein addresses many of the concerns of array reconfiguration in a context suitable to integration with portable devices. Like most PV cells and arrays, the TDAR system extracts maximum power from each cell, but it does so using analog circuits, which ultimately reduce power consumption, size, and weight of the energy harvesting system. Array reconfiguration is then used to make the most of MPP tracking, allowing maximum power to be extracted from the array with minimal losses. The unique benefit of the TDAR approach lies in its ability to reconfigure the system