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Solar Energy xxx (2010) xxx–xxx
SOLAR ENERGY
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Toward integrated PV panels and power electronics using printing technologies

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Received 1 October 2009; received in revised form 15 March 2010; accepted 16 March 2010

Communicated by: Associate Editor Arturo Morales-Acevedo

Abstract

In this paper, we review the latest developments in the area of printing technologies with an emphasis on the fabrication of control-embedded photovoltaics (PV) with on-board active and passive devices. We also review the use of power converters and maximum power point tracking (MPPT) circuits with PV panels. Our focus is on the investigation of the simplest implementations of such circuits in view of their integration with solar cells using printing technologies. We see this concept as potentially enabling toward further cost reduction. Besides a discussion as to feasibility, we shall also present some projections and guidelines toward possible integration.

Keywords: Photovoltaics; Printing technology; Maximum power point circuit; DC/DC converter

1. Introduction

The International Energy Agency (2010) estimates that worldwide investments in energy supply will total approximately 22 trillion dollars by 2030. Photovoltaics (PV) markets will account for a growing proportion (estimated at 10–20%) of this investment in the comming years (Kimbis, 2008). A recent report (IDTechEx, 2009) forecasts that the market for printed electronics, including organics, inorganics and composites, will rise from $1.92 billion in 2009 to $57.16 billion in 2019. It is projected that there will be a rapid growth of PV, OLEDs (on glass) and e-paper displays followed by mixed organic and inorganic thin film transistor circuits (TFTCs), flexible OLEDs, sensors and batteries.

The slow adoption of large-scale deployment of solar cells has been attributed to the higher cost ($/W) compared to other more traditional energy technologies. This cost includes both the cost of fabrication (including materials and manufacture) and the cost of installation, maintenance and field repair over the life time of PV systems. We propose a design solution space defined by three performance attributes where implementation may be cost-engineered to meet particular overall system requirements. These attributes define the three dimensions of design space as absorber technology, MPPT method, and converter type (Fig. 1). This model illustrates that to attain targeted cost/performance metrics, the design solution will require trade-offs among the converter efficiency, the accuracy and tracking speed of the MPPT circuitry, and the photovoltaic performance of the absorber technology. The tracking speed characterizes the convergence rate of the MPP algorithm subject to sudden changes of irradiance. It is a measure of the robustness of the MPPT circuit against variations in atmospheric conditions.

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doi:10.1016/j.solener.2010.03.016

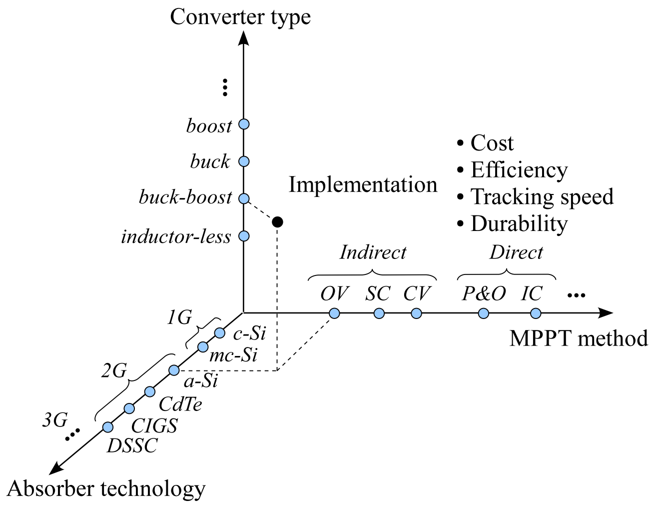

Fig. 1. Design solution space representation. For a given application,the PV system implementation will represent a point in this three-dimensional space.

We use this representation in the remainder of this paper and present a general review of the main results along the three dimensions. Because each of these three directions is extensively covered in the published literature we will include only a minimal number of references in order to build our discussion. Rather than providing a detailed review of previous work on these topics, our goal is to discuss recent and relevant advancements in order to identify trends and arrive at several design guidelines that integrate power electronics with solar cells toward cost-effective system manufacture. For more comprehensive surveys on individual topics (e.g., PV and printing technologies, MPPT and DC/DC circuits), the reader is referred to (Das, xxxx; Green et al., 2009; Miles et al., 2005; Shrestha, 2009; Krebs, 2009; Granqvist, 2007; Salas et al., 2006) and the references therein.

2. Fabrication technologies for photovoltaics

While the great majority of fielded PV use crystalline silicon prepared from the melt, we discuss mainly non-crystalline silicon based fabrication technologies. While the majority of the reports for thin film semiconductor relate to vacuum-based growth, we posit that future developments in atmospheric-pressure, low-temperature processing shall become increasingly relevant to economic manufacture. As such, we also include in our discussion printing technologies from other application domains, which can become candidates for *technology cross-breeding* with PV technologies in view of integrating solar cells and power electronics.

2.1. Photovoltaics and thin-film transistors

The first generation (1G) of PV technologies is primarily dominated by single-junction solar cells based on silicon wafers including single crystal (c-Si) and multi-crystalline silicone (mc-Si) (Bagnall and Boreland, 2008). While 1G technologies offer efficiencies of 18–21%, the cost of manufacture remains high. Second generation (2G) technologies (whose market share is expected to reach 25% of the total PV market by 2010, van Sark et al., 2007) are aimed to ward cost reduction by employing thin-film fabrication processes previously developed for semiconductor device manufacture. Even though currently 2G technologies achieve lower energy conversion efficiencies, they offer several benefits including simple fabrication on flexible substrates (hence low fabrication cost) and the ability to coat semiconducting absorber layers over large areas.

In the following paragraphs, we review recent advancements in 2G solar cell technologies and also discuss the use of these thin-film semiconductors as thin-film transistors (TFT). A premise of this report is that the same thin-film semiconductor could be used in both the absorber layer and the power electronics transistors thereby simplifying the manufacturing process. Table 1 is a summary of 2G thin films that are used in solar cells and transistors with data compiled from several overview papers (Zervos, 2009; Keyes, 2007; Roedern et al., 2006; Jager-Waldau, 2004; DOE, 2009). With the exception of a-Si, there are many more reports related to thin-film PV than transistors. We point out that while our definition of 1G technologies are limited to crystalline and/or polycrystalline Si, the ability to form thin films of crystalline silicon on glass (CSG) (Green et al., 2004) and polycrystalline silicon on glass (Green, 2009; von Roedern et al., 2008) have been of recent interest. Moreover, 1G silicon technologies are now being used in novel ways as exemplified in the work of Rogers and collaborators (Yoon et al., 2008; Kim et al., 2009; Baca et al., 2010). Each of the 2G technologies presented in Table 1 is now briefly reviewed.

Amorphous silicon (a-Si) is the most popular thin-film technology (pursued since late 1970s). It was the main incumbent technology for TFTs, which has grown into a huge industry based on display applications (Street, 2009). There have been numerous TFT fabrication processes reported in the literature. Recently, processes based on letterpress printing from flexible polyimide stamps were studied in (Miller et al., 2003). Polyhydrosilane precursor inks have been used in the formation of a-Si thin films by Seiko-JSR (Shimoda et al., 2006) and NDSU (Han et al., 2008). The Shimoda project (Shimoda et al., 2006) team spun-coat 50 nm thick transistors from cyclopentasilane with mobility of 108 $cm^2/V\,s$ and a seven digit on/off ratio. NDSU has recently employed cyclohexasilane in an aerosol-based deposition route to a-Si films 250 ± 125 nm thick and 7 ± 1 μm in width (Schulz et al., in press) and this collimated aerosol-beam direct-write technique affords resolution to 5.0 ± 0.5 μm given appropriate process control (Akhatov et al., 2008). Silane-based inks that contain ultra-small crystals of silicon might be considered a

Table 1
Overview of thin-film technologies as second generation (2G) of PV technologies.

Thin-film[a] technology	Module ($/W)/ installed ($/W)	Thin-film market (%)	Efficiency (%)	Area[b] (cm^2)	V_{OC}[c](V)	J_{SC}[d](mA/cm^2)	FET W/L	Benefits	Challenges
Amorphous silicon (a-Si), nanocone silicon	<2/4.5	61	8–10	1.070	0.859	17.5	10–400 μm/ 1.5–40 μm	Thin-film, flexible substrates, roll-to-roll processing	Long-term instability
Cadmium Telluride (CdTe)	1.25/4.5	34	9–16	1.032	0.845	26.1	1000 μm/ 5 μm	Good efficiency	Cd toxicity, controlled disposal
Copper Indium Gallium Diselenide (CIGS)	<2/6.3	4	10–19	0.994–16.0	0.661–0.716	33.6–33.7	n.a.	High efficiency, low-cost, high absorption	Price of indium, process stability
Dye Sensitized Solar Cells (DSSC)	<3/n.a.	1	11	1.004	0.729	22.0	n.a.	Tolerant to low level light, choice of colors, high absorption	Liquid electrolyte, price of ruthenium, poor charge mobility
Organic polymer	0.7/n.a.	n.a.	2–5	1.021	0.876	9.39	100 μm–3 mm/ 4–150 μm	Potentially lowest cost, large-scale possible	Low efficiency, high cost, instability, narrow spectrum

[a] The data presented in this table is compiled from tables reported in (Green et al., 2009; Zervos, 2009; Keyes, 2007; Roedern et al., 2006; Jager-Waldau, 2004; DOE, 2009). The information is intended to give a qualitative overview of the current status. These technologies are evolving and new results are continuously reported and periodically updated in focus studies such as (Green et al., 2009; Shrestha, 2009).
[b] Aperture area.
[c] Open-circuit voltage.
[d] Short-circuit current density.

1G variant and are not reported. High voltage thin-film transistors (HVTFT) were successfully integrated with MEMS on glass substrates where gate lengths of 9 μm and widths of 10 μm were reported (Chow et al., 2006).

Cadmium Telluride (CdTe) is a stable and inert semiconductor that offers good solar conversion efficiencies especially in low and diffuse light conditions. It can be fabricated by sputtering, high throughput vapor transport method (McCandless et al., 2005), electrodeposition (Lepiller et al., 2000), closed-space sublimation (Romeo et al., 2010), and dip technique using succinic acid (Hankare et al., 2009). However, cadmium is toxic and the availability of tellurium can become a cost-limiting issue (Fthenakis, 2009). Nevertheless, First Solar recently announced their close-space sublimation route to thin-film CdTe solar cell manufacture eclipsed the long-standing cost target of $1/W (First Solar Passes $1 Per Watt Industry Milestone, 2009). Abound Solar, a spinout from Colorado State University, has also recently announced the ability to produce CdTe solar cells at less than $1/W (Wilmsen, 2009). TFTs with better charge mobilities were created using CdTe/CdHgTe nanocrystals synthesized by the colloidal method and width over length ratio values of $W/L = 1000\ \mu m/5\ \mu m$ were reported in (Kim et al., 2007).

Copper Indium Gallium Diselenide (CIGS) is a compound semiconductor material composed of copper, indium, gallium, and selenium. CIGS solar cells can be fabricated by sputtering, spray pyrolysis, electrodeposition, molecular beam spectroscopy, and physical vapor deposition (Thompson et al., 2008). Several companies including Global Solar, Ascent Solar, International Solar Electric Technology, Unisun and Heliovolt are in the process of manufacturing CIGS-based solar cells. Because of the promising high efficiency of CIGS cells and the potential to generate cost-effective PV electricity, it appears increasingly likely that CIGS thin films will have a great impact on the development of photovoltaics in the future (Noufi and Zweibel, 2006,). Nevertheless, we could not find any reported results on the use of CIGS-based materials to create transistors.

Dye Sensitized Solar Cell (DSSC) is a fundamentally new type of device based on small particles (with diameter of 20 nm) coated with a thin layer of pigment (Graetzel, 2005; Graetzel, 2008; Lenzmann and Kroon, 2007). It can be fabricated as flexible sheets, is mechanically robust, and has good potential for lowering costs. However, apart from its somewhat lower efficiency, it still faces difficult issues related to poor charge mobility and device stability.

Organic or polymer based solar cells use thin films of organic semiconductors (Krebs, 2009; Kim et al., 2009; Bejbouji et al., 2010; Knobloch et al., 2004). They can be fabricated using large area coating or continuous printing processes.

Please cite this article in press as: Ababei, C. et al. Toward integrated PV panels and power electronics using printing technologies. Sol. Energy (2010), doi:10.1016/j.solener.2010.03.016

TFTs based on organic materials have been widely studied due to low-cost, low-temperature, and simple processes on plastic substrates that enable flexible electronic devices. However, their main limitations include lower efficiency and lower current density. Organic and polymer transistor based circuits have been investigated for applications such as display switches, display drivers, radio-frequency identification (RFID) tags, and sensors (Dodabalapur, 2006). Companies like PolyIC, EInk, Kent Displays and others have already moved to large-scale manufacture of printed polymer/organic electronics in these application domains. Challenges of printing methods include non-uniformity of the film and imperfect contact with other layers, which result in the degradation of performance of the TFTs. Kim et al. (2009) addressed these issues by adjusting the solvent mixture ratio and reported a channel width over length ratio of $W/L = 400\ \mu m/15\ \mu m$. Tobjork et al. (2008) used reverse gravure (RG) to apply the semiconductor and insulator layers in a continuous roll-to-roll technique with the electrodes inkjet-printed to achieve hygroscopic insulator FETs on plastic substrates. They reported a channel width over length ratio of $W/L = 1.5\ mm/40\ \mu m$ and changes in the channel conductance after 48 days. Park et al. (2009) reported the fabrication of inkjet-printed n-type organic thin-film transistors (OTFTs) based on a C_{60} derivative. They reported a channel width over length ratio of $W/L = 3\ mm/50\ \mu m$. Other previous work reported W/L ratios of $100\ \mu m/4\ \mu m$ (Vaillancourt et al., 2006), $3\ mm/5\ \mu m$ (Kawase et al., 2005), and $236\ \mu m/6\ \mu m$ (Lee et al., 2008), achieved using inkjet printing.

Even though organic electronics has been the subject of extensive research and functional all-polymer integrated circuits have been created (Matters, 1999; Klauk et al., 2005), many issues still need be addressed in view of the successful large-scale integration of digital and analog circuits. Some of these issues are balancing the mobility of p- and n-type transistors, scaling down lateral dimensions, and device modeling and circuit design (Bartzsch et al., 2007; de Leeuw and Cantatore, 2008).

2.2. Interconnections, capacitors, inductors and resistors

Printing methods can also be used to create interconnections and passive devices (see Table 2). Schulz et al. (2001) employed an air-reactive liquid Cu(hfa)VTMS metal-organic (a chemical vapor deposition precursor trademark Cupraselect^{TM}) as the ink for spray deposition of Cu and observed that 350 nm thick films grown at temperatures $\sim$230 °C exhibited resistivities as low as $24 \pm 14\ \mu\Omega\ cm$ (i.e., $\sim$10 times bulk Cu). Kim et al. (2009) introduced a copper nano-ink with a drop-on-demand (DOD) piezoelectric inkjet printing method. They adhesively joined an amorphous silicon solar cell and a thin-film solid state lithium-ion battery and then they electrically connected them to a thin flexible printed circuit board (PCB). Resistors and diodes were electrically connected to the printed circuit board by silver pasting. Insulator and nano-sized copper particles based conductive inks were studied by Kumashiro et al. (2009). Metalization of copper trace was done with atomic hydrogen. The conductivity of the copper trace was 3 μΩ cm. Transparent conductors (TC) can be printed and will be especially useful in PV systems (Granqvist, 2007). Inkjettable dielectric and conductive materials on a substrate having embedded components were demonstrated in (Miettinen et al., 2008) to manufacture electronic modules. The main materials used for printed interconnects include copper (Cuk et al., 2000), aluminum, gold (Redinger et al., 2004) and silver (Kim, 2009).

Table 2
Overview of technologies for interconnections, capacitors, inductors, and resistors.

Item	Characteristics	Material, process
Interconnections	Line width: 60–320 μm	Cu, Au, Ag, Al Inkjet printing, laser scribing, evaporation
Capacitors	Capacitance: 42 pF–70 nF	Polymers, nanocomposites, ceramic oxide
	Area: 600 μ×600 μ–4 cm^2	Printing, photolithography Sputtering, sol–gel, atomic layer deposition, rotogravure
Inductors	Inductance: 3 nH–12.7 μH	Au, polymers, ferrite nanopowders
	Quality factor: 2.5–45	Printing, hydrothermal
	Line width: 160 μm–5 mm	
Resistors	Resistance: <10,000 Ω/□	Ceramics, polymers Screen/inkjet/plasma printing, sequential lamination Sputtering, laser trimming, lithography Chemical etching

Development of thin-film magnetic materials and design and fabrication processes for passive devices have been the subject of numerous studies (Redinger et al., 2004; Klee et al., 1998; Min, 2005; Cui et al., 2005; Namsoo et al., 2009; Kostka and Abhari, 2009). For example, an all inkjet-deposited process capable of creating high-quality passive devices suitable for RFID front-ends was described in (Redinger et al., 2004). The authors reported gold lines up to 2.5 μm thick and inductors with radii of 5000 μm, line widths of 160 μm, line spacing of 10 μm, and quality factor (Q) of 0.5 at 13.5 MHz. An effective way to improve the operating frequency and quality factor of thin-film inductors was proposed in (Tang et al., 2004). Planar capacitors (3.1 nF on 4 cm^2) and resistors (25, 50, 75 and 100 Ω) were embedded on a prototype PCB base using sequential lamination technique (SLT) (Lee et al., 2008). Polymer screen-printed resistors with values up to 1150 Ω were reported in (Cheng et al., 2007). All-polymer capacitors (338 pF on 4 mm^2) have been created by inkjet printing (Liu et al., 2003).

While the general consensus in embedded passives is that the resistor technology (resistivity 25–10,000 Ω/□) is viable, capacitor technology (up to 70 nF/cm^2) needs further investigation and development in order to achieve wide capacitance ranges (from few pF to μF range) required for a variety of functions (Jain and Rymaszewski, 2002; Raj et al., 2007).

2.3. Discussion

Using the degree of integration of PV panels with power electronics, we identify several design approaches:

- *No integration*. PV panels and power electronics are designed and manufactured using separate technologies. Complete PV systems are then built in the field using custom approaches. This approach is expensive to build and maintain.
- Module integrated converter (MIC) is a solution where the two components fabricated separately are combined and deployed on the same frame (Masato et al., 1998; Sahan et al., 2008; Linares et al., 2009; Linares et al., 2009; Erickson et al., 2009).
- *Hybrid integration*. In this approach, most of the power electronics are fabricated using the same printing technology as the solar cell, preferably on the back of the substrate. Components that cannot be realized using printing technologies (such as power transistors, diodes, inductors, large capacitors, etc.) can be integrated as surface mounting devices or as embedded or integrated product designs (IPDs) (Kim et al., 2009; Miettinen et al., 2008).
- *Full integration*. In this projected idea, the power electronics will be fabricated using the same printing fabrication technology as the solar cells. Because in this approach the cost of power electronics will be reduced, the MPPT circuit could be integrated with solar cells. The benefits of this idea include versatility of PV panels that could output DC or AC depending upon the type of integrated converter and optimal output power at solar cell level. They will also make the overall PV system more efficient and robust to changes in environmental conditions.

If past research related to the 1G and 2G technologies focused primarily on the continuous improvement of conversion efficiency and the development of materials (other than silicon) to allow higher efficiencies or lower costs, future (3G) technologies research efforts will also have to consider the feasibility of the integration of solar cells with power electronics. Currently, it is unclear how 3G innovations such as optical metamaterials (e.g., self organized nanostructured glass), multi-junction devices (e.g, triple junction cells), or nanosilicon materials will allow full integration as a means to reduce costs.

Moreover, because CdTe, CIGS and DSSC PV cell technologies are relatively young, their use in solar cells still faces several challenges including long-term stability, control, and process cost (Noufi and Zweibel, 2006,). Hence, they have been less favored in the fabrication of FETs and passives. On the other hand, a-Si and organic polymers have been extensively used to create FETs, inductors, and other devices, and we expect them to become better candidates for printed electronics integrated with solar cells in the near future. Organic-based solar cells suffer from low efficiency, which will have to be increased beyond the 10–15% range, in order to become more cost effective and to truly exploit the printing-friendly properties (Kalowekamo and Baker, 2009).

In summary, currently no one technology can meet the entire range of required performance metrics for photovoltaics, transistors, resistors, capacitors, and inductors. Hence, it is likely that more than one technology will have to be employed in a hybrid approach such as using CIGS for photovoltaics (to achieve high efficiencies) and a-Si or organic printing for active and passive devices (with some of these being embedded or integrated) for power electronics.

3. Maximum power point tracking circuits

The simplest PV system connects the PV panel directly to the load in a stand-alone configuration (other configurations are grid-connected or hybrid systems). In this case, the operating point of the system is at the intersection between the *I–V* characteristic of the PV panel and the load line. Because the *I–V* curve is affected non-linearly by the irradiance level and temperature of the panel, and given that the load impedance is generally not constant, the operating point could be far away from the maximum power point (MPP) that corresponds to maximum efficiency. It is to be noted that ensuring maximum efficiency is another way of reducing the cost of PV systems. Note that, even though irradiance affects mainly the output current with temperature affecting mainly the voltage (Salas et al., 2006), the *P–V* curve may be affected by other factors such as incidence angle, wind vector, atmospheric-pressure, and absolute humidity (Salas et al., 2005; Mousazadeh et al., 2009). To address this, an appropriate algorithm must be utilized to track the MPP and a charge controller must be inserted between the PV panel and load (battery). This can be implemented by a DC/DC converter that is controlled by additional circuitry (e.g., pulse-width modulation (PWM) controller) to facilitate the seeking of the MPP as shown in Fig. 2. Such controlled DC/DC converters are called maximum power point trackers (MPPT). The definitions of the variables from Fig. 2 are presented in Table 3.

The role of such an MPPT circuit is to match the PV panel and the load (typically includes a battery) so that the PV panel operates at MPP and the load receives the desired constant voltage. The DC/DC converter creates an impedance transformation (i.e., variable resistance emulation) through the duty cycle such that the input

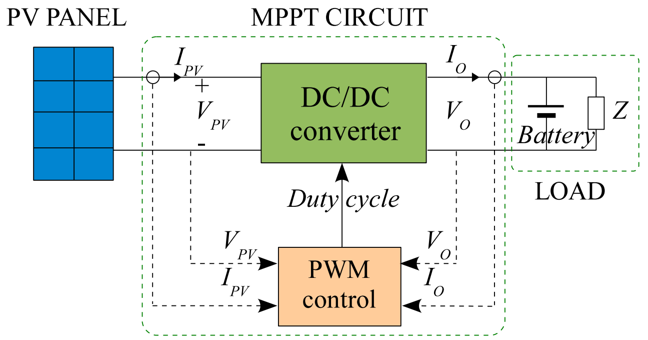

Fig. 2. Block diagram of a stand-alone PV system using an MPPT circuit.

Table 3
Variables of the MPPT circuit.

Variable	Definition
V_{PV}	PV panel output voltage (DC/DC converter input voltage)
I_{PV}	PV panel output current (DC/DC converter input current)
V_{MPP}	Maximum power point voltage
I_{MPP}	Maximum power point current
V_{OC}	Open-circuit voltage
I_{SC}	Short-circuit current
V_O	DC/DC converter output voltage
I_O	DC/DC converter output current

impedance (seen by the PV panel toward the converter) corresponds to the panel's MPP for any load impedance or panel operating condition. This is achieved by controlling the length of the time interval the main converter switch is "on" (PWM technique) typically at a constant frequency. The ratio of the "on" interval and period is called the *duty cycle* of the converter. The losses incurred by the MPPT circuit should be small in order to get a high efficiency for the overall system. Its cost should also be small.

3.1. PV cell modeling

In this section we briefly review the most commonly used PV cell modeling, which has been the subject of research for over two decades, due to its use in PV systems design. This review will also be helpful for our discussion of MPPT circuits later in the paper. Manufacturers typically provide several PV panel parameters for an irradiance of 1000 W/m^2 and panel temperature of $T_{ref} = 25\,°\mathrm{C}$. Examples of such parameters are the open circuit voltage V_{OC}, short circuit current I_{SC}, the MPP voltage, and current V_{MPP}, I_{MPP}, the temperature drift coefficients for open circuit voltage $\beta_{V_{OC}}$ and short circuit current $\alpha_{I_{SC}}$. In order to design MPP tracking circuits, one needs to accurately model the PV panel behavior under variable working conditions. SPICE models are the most popular and Fig. 3 presents a typical equivalent lumped circuit model (Phang et al., 1984; Townsend et al., 1989; Gow and Manning, 1999; Kiranmai and Veerachary, 2005; Dondi et al., 2007; De Soto et al., 2006) for a PV panel. In this model, the current source I_{ph} represents the light generated current

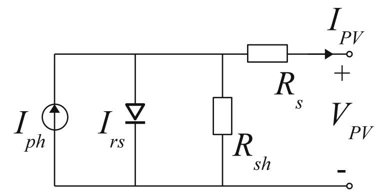

Fig. 3. Equivalent lumped model circuit of the PV panel.

and the diode accounts for the knee of the current-voltage relation through the reverse saturation current $I_{rs} \cdot R_s$ is a series resistor and R_{sh} is a shunt resistor which model the intrinsic losses. These model parameters are functions of the irradiance and temperature of the panel.

The current–voltage relationship at a fixed temperature and solar radiation can be obtained using Eq. (1) (De Soto et al., 2006):

$$I_{PV} = I_{ph} - I_{rs}\left(e^{\frac{V_{PV}+I_{PV}R_s}{a}} - 1\right) - \frac{V_{PV} + I_{PV}R_s}{R_{sh}} \quad (1)$$

In a first approximation, R_s is negligibly small and R_{sh} is relatively large, and Eq. (1) becomes:

$$I_{PV} = I_{ph} - I_{rs}\left(e^{\frac{V_{PV}}{a}} - 1\right) \quad (2)$$

The PV panel output power P_{PV}, which is used to calculate the MPP setting $dP_{PV}/dV = 0$, is given by Eq. (3) as:

$$P_{PV} = V_{PV} \cdot I_{PV} = V_{PV} \cdot \left[I_{ph} - I_{rs}\left(e^{\frac{V_{PV}}{a}} - 1\right)\right] \quad (3)$$

where $a = \frac{N_s \eta k T}{q}$ represents the modified panel ideality factor, and q is the electron charge, k is the Boltzman's constant, η is the PV single cell ideality factor (with values between 1 and 2), N_s is the number of cells in series, and T is the PV panel temperature.

The component values of this lumped model are related to the PV panel characteristics and several methods, for example, have been proposed to extract them by using analytical or empirical relations. The characterization of the PV panel obtained in this way depends on the fabrication technology and the environmental working conditions (Townsend et al., 1989; Kiranmai and Veerachary, 2005; De Soto et al., 2006) as follows:

$$I_{rs} = I_{rs,ref}\left[\frac{T}{T_{ref}}\right]^3 e^{\frac{qE_g}{\eta k}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \quad (4)$$

$$I_{ph} = S \cdot I_{SC,ref} + \alpha_{I_{SC}}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right) \quad (5)$$

where $I_{rs,ref}$ is diode reverse saturation current at the reference temperature T_{ref}, E_g is the band-gap energy of the material, S is the solar irradiance (W/m^2), and $I_{SC,ref}$ is the short circuit current at reference condition. Eqs. (1) and (3) are used to plot the I–V and P–V curves for different irradiances and temperatures. Typical curves for different irradiances are shown in Fig. 4. It should be noted that the I–V characteristics of PV modules are different for different technologies (Dobrzanski et al., 2006). This is

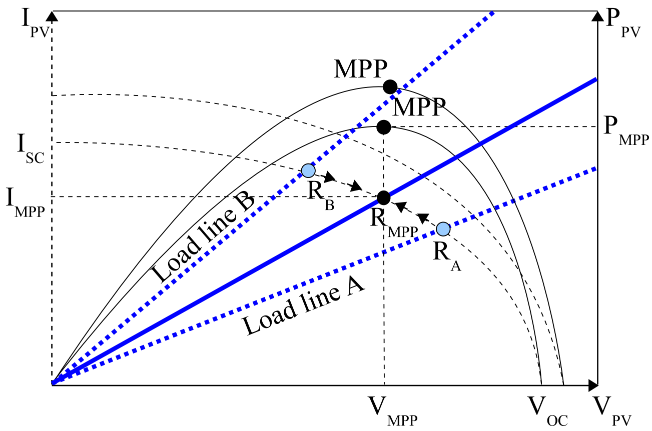

Fig. 4. Typical *I–V* and *P–V* curves. The load line (i.e., the converter input resistance) should be crossing the *I–V* curve at MPP for maximum efficiency. Only the buck-boost converter based MPP tracking circuit can move this load line from either point R_A or R_B to point R_{MPP} as indicated by the arrows (Enrique et al., 2007).

assumed to be taken into consideration during the design of power electronics that will be integrated with PV modules. Because the underlying problem of tracking the maximum power point remains the same across different technologies, we consider this not to have a significant impact on the major design decisions regarding the integration discussed in this paper.

3.2. Classification of MPPT circuits

There have been considerable efforts to develop MPPT topologies and, as a consequence, we found a large number of papers on this topic. We recommend the reader to consult (Salas et al., 2006; Faranda and Leva, 2008; Esram and Chapman, 2007; Enrique et al., 2007; Pandey et al., 2007) and their references for recent surveys. Typically, MPPT algorithms use as input two variables V_{PV}, I_{PV} (see Fig. 2) but algorithms using only one variable have been also proposed. According to the control strategy for seeking the maximum power point, there are two categories of MPPT methods: **direct** and **indirect** (Salas et al., 2006).

Examples of **indirect (*quasi seeking*) methods** are: curve fitting (Takashima et al., 2000; Hua et al., 2003; Nishioka, 2003), look-up table (Ibrahim et al., 1999), open circuit voltage (OV) (Masoum et al., 1998; Masoum et al., 1999; Veerachary et al., 2002; Lee et al., 2002; Pandey et al., 2007), short current PV generator (SC) (Alghuwainem, 1994; Noguchi et al., 2002; Yuvarajan et al., 2004), constant voltage (CV) (Yu et al., 2002), and the open circuit voltage PV test cell (Salameh et al., 1991). These methods are based on the use of a database that includes typical *P–V* curves for different irradiances and temperatures or on the use of mathematical functions to estimate the MPP from empirical data (Salas et al., 2006). For example, some of the OV methods are based on the approximation that the maximum power point voltage V_{MPP} is located at 76% of the open circuit voltage V_{OC} (Pandey et al., 2007; Leyva et al., 2006). On the other hand, some of the SC methods assume that the maximum point current I_{MPP} is approximately 92% of the short circuit current I_{SC} (Noguchi et al., 2002; Yuvarajan et al., 2004). While these approximations offer references for the PV output to track, they are accurate only for certain parameters of the *I–V* and *P–V* curves. Because the indirect methods estimate rather than obtain a true value of MPP, they are not versatile with respect to the load profile or changes in the atmospheric conditions. They may require memory circuits, but are simpler and possibly cheaper to implement.

Examples of **direct (*true seeking*) methods** are: differentiation, feedback voltage/current (Maheshappa et al., 1998), quadratic approximation (Chao et al., 2009), perturbation and observation (P&O) (Salameh and Taylor, 1990; Hua et al., 1998; Kuo et al., 2001; Hsiao et al., 2002; Wu et al., 2003; Liu and Lopes, 2004; Femia et al., 2006; Kim et al., 2006; Leyva et al., 2006; Sera et al., 2006; Cabal et al., 2007; Chu and Chen, 2009), incremental conductance (IC) (Hussein et al., 1995), parasitic capacitance (Branbrilla et al., 1999), only current PV (Salas et al., 2005) and forced oscillations (Tse et al., 2001). Their advantage is that no prior information of the PV characteristics is required. These methods are versatile with respect to the load profile, can offer flexibility of reconfiguration of the MPPT algorithm if a microcontroller is used, but require PV voltage and/or current measurements (Salas et al., 2006).

The efficiency of a PV system depends on the type of DC/DC converter and the MPPT technique. The MPPT techniques vary in terms of simplicity and of hardware implementation, cost, convergence speed (hence robustness to variations of irradiance and temperature), sensors requirement, range of effectiveness, and need for parametrization (Faranda and Leva, 2008). Therefore, one needs to judiciously select the appropriate MPPT circuit and make the right design decisions to best serve the application at hand. Because direct MPPT techniques are more precise in tracking the maximum power point, they offer better efficiency (Berrera et al., 2009). The performance of the MPPT circuit depends on the type of DC/DC converter as well as on the MPPT algorithm that is used. Recently, it has been reported that there is a limitation to system performance according to the type of converter used (Enrique et al., 2007). That is primarily due to the fact that optimum converter input impedance values cannot be reached (therefore affecting the ability to track the MPP), for certain types of converter (see Fig. 4). It was found that the buck-boost DC/DC converter circuit is the only configuration that allows the follow-up of the PV module MPP regardless of temperature, irradiance, and connected load. Moreover, the buck-boost DC/DC converter achieves the highest efficiency (99.9%) compared to buck (97.2%) and boost (91.2%) converters for a load of $R_L = 5\,\Omega$ (Enrique et al., 2007).

Another factor in determining the MPPT technique of choice is the level of voltage or current desired. This is closely related to and depends on the application domain. For

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example, in portable applications (where the voltage level is very low), indirect MPPT methods are preferred also due to the required low packaging-volume and cost. Because, at high voltage and current levels the MPPT circuits will require high voltage and current devices (which in turn will require large integration areas), we assume that the concept of integration discussed in this paper will be applied at low voltage and current levels. That is, MPPT circuits will be integrated at the solar cell (and possibly module) level rather than module/panel and array levels. Then, connection to the load or grid could be done using an approach similar to that studied in (Roman et al., 2008).

The concept of integrating a converter into each PV module/panel – called module integrated converter (MIC) – has been discussed in the recent literature as a hybrid system, where the two components fabricated separately would be combined and deployed on the same frame (Masato et al., 1998; Sahan et al., 2008; Linares et al., 2009; Linares et al., 2009; Erickson et al., 2009). In this paper, we take this idea a step further, and discuss the possibility of integrating the MPPT circuit with the solar cell by manufacturing both using the same fabrication technology. The goal of such integration is to further reduce the cost of PV systems by using the same printing technologies to fabricate all the required MPPT components on a small area or on the back-side of the solar cell. Such integration would facilitate versatile plug-and-play PV cells that would be easy and cheap to mount and to maintain in large scale PV systems. Because each cell would have its own integrated MPPT circuit, the output power is optimal locally. This is an effective way to address varying irradiance (due to changing atmospheric conditions) for large area PV systems. To achieve this goal, the MPPT circuit has to be very simple, ideally implemented using a minimum number of active and passive devices (for minimum area) without expensive microcontrollers, DSPs, Op-Amps, and so on, which are harder to integrate using printing technologies. This integration idea was discussed by Roshau (2009) who has also proposed a simple MPPT circuit designed using a buck-boost converter and an open circuit voltage (OV) MPP tracking technique (Roshau, 2009). The MPPT circuit is designed using only active and passive devices (10 MOSFETs and 30 passives without counting the buck-boost converter). A drawback of this MPPT circuit as of most others is that it requires a 10 V power supply. Ideally, the MPPT circuit should draw its power from the PV panel and/or the charged battery of the PV system, especially in mobile or wireless sensor nodes applications. In order to achieve that, the MPPT circuit should consume substantially less power than the amount of output power that it delivers. For example, an elegant MPPT solution using the OV method was presented in (Brunelli et al., 2008).

Another challenge toward the integration of the MPPT circuit with the solar cell is the fact that typical DC/DC converters require large inductors, which may be difficult to create using CMOS based or printing technologies and which can occupy large areas. There are however several inductor-less MPPT solutions proposed recently (Shao et al., 2009; Shao et al., 2007), which can be used toward creating simpler and cheaper integrated solutions. Other circuit simplifying ideas can be found especially in the literature related to portable applications, where the main goal is to reduce the circuit size and power consumption (Chao et al., 2007; Park and Chou, 2006).

3.3. Discussion and design guidelines

Based on our review so far, we identify the following design guidelines for MPPT circuits:

- If the best efficiency and total versatility with respect to the load profile or changes in the PV parameters is desired, then direct MPPT methods are the main choice (Salas et al., 2006). These methods can also offer flexibility of MPPT upgrade when a microcontroller is used to implement the MPPT algorithm (Rizzo et al., 2009). Moreover, from among the direct methods, the perturb and observe (P&O) technique was experimentally found to be offering the best efficiency (Berrera et al., 2009). However, these MPPT topologies may become expensive to implement because they typically require the use of microcontrollers and direct measurements of PV voltage and/or current. Nevertheless, circuit simplifications are possible in order to reduce circuit complexity and therefore costs. For example, one can use only methods that involve PV current (Salas et al., 2005) or voltage (Pandey et al., 2007) measurements.
- The design of the MPPT circuit is a multiobjective problem: one would like a solution with the best efficiency at the lowest cost. However, it is evident that there is a trade-off between these two objectives. Therefore, if the cost rather than efficiency is a more important design concern, then indirect methods are better candidates. For example, the constant voltage (CV) technique provides a very good efficiency with a very simple logic (Faranda and Leva, 2008; Berrera et al., 2009). Similarly, the open circuit voltage (OV) technique can offer reasonable performance using pilot photo cells without a microcontroller, especially for small-scale PV systems or mobile applications (Brunelli et al., 2008; Roshau, 2009; Itako and Mori, 2005) where small volume and lower power consumption are desirable. However, the efficiency will be less compared to direct methods. Because for large-scale PV systems, volume and circuit power consumption are not as critical, direct MPPT methods have been commonly used. However, in order to achieve integration, MPPT circuits will have to be simplified and implemented without microcontrollers and other complex devices that are too big to be fabricated using printing technologies. Efficiency will be smaller, but this could be addressed by tuning the level of granularity at which the PV cells and panels are equipped with integrated MPPT circuits.

- Because the ability to track MPP across the possible ranges of irradiance and temperature depends on the type of converter topology used, the buck-boost DC/DC converter should be the preferred choice (Enrique et al., 2007). This converter configuration is, for example, used in the implementation proposed in (Roshau, 2009). Another design aspect is related to the configuration of larger PV systems created using smaller PV panels (each with its own integrated MPPT circuit). For instance, if a parallel configuration is chosen in order to charge a battery, then the converter must be regulated using the output current as control variable (Pernia et al., 2009).
- If the technology used cannot provide cheap and compact integrated inductors, then inductor-less solutions may be a viable option (Shao et al., 2007). Also, in stand-alone PV systems (portable devices or wireless sensors), MPPT circuits that can be powered from either the PV panel or from a rechargeable battery are desirable, such as the solution presented in (Brunelli et al., 2008). Inductor-less and OV MPPT circuits seem to be especially good candidates for the integration of power electronics with PV panel using the same fabrication printing technologies.

Finally, we would like to point out several aspects that will have to receive more attention.

- The trade-off between the complexity of the MPPT circuit and the achievable robustness to rapidly changing irradiance or temperature is still unclear. Metrics for the robustness of the MPPT methods to such variations and design techniques to minimize the oscillations around the MPP are still needed.
- Better stability analysis techniques for extremum-seeking MPPT algorithms are needed. Most of the reported MPPT algorithms require a stability guarantee for the feedback system (which has been typically verified but not analytically proved). The Lyapunov technique reported in (Leyva et al., 2006) is a recent effort in this direction.
- Particularly needed are better design methodologies. Traditionally, MPPT circuits and PV systems have been designed manually or relying extensively on designer's experience and creativity. However, simple yet accurate Spice models integrated with automated design tools can offer significant cuts in cost and design time (Dondi et al., 2007; Brunelli et al., 2008).
- Reliability of MPPT circuits should represent a design concern too. Today, most of the MPPT topologies are not developed taking reliability into account. However, reliability is especially important in PV applications where the thermal stress rather than complexity of the system can affect the long-term performance (Sahan et al., 2008; Chan and Calleja, 2006; Puc and Gjumlich, 2008; Liu et al., 2009; Dhople et al., 2009).
- For each fabrication technology, a detailed cost analysis of the integration approach is necessary. One needs to investigate whether an MPPT circuit is worth integrating at solar cell, module/panel or array level. The benefits in terms of overall PV system efficiency and its robustness to irradiance changes will have to be weighed against the cost of MPPT circuits and the right trade-off should be found.
- Last but not the least, a better examination of environmental issues should constitute an integrated part of development of comprehensive technologies and products (Fthenakis, 2009). More information on the new materials and further optimization (Logothetidis, 2008) of the manufacturing process are required before electronics printing can be claimed to be environmentally friendly (Miles et al., 2005; Kunnari et al., 2009).

4. Conclusion

In this review paper, we discussed the full integration of power electronics with solar cells using printing technologies as a potential concept toward further cost reductions of PV systems. We identified the fabrication technology, the type of DC/DC converter, and the MPPT method as the main dimensions of the design solution space of PV systems. Using this representation, we discussed recent research advancements and arrived at several design guidelines that could be pursued toward a possible long-term integration. However, in the near future, it is likely that more than one technology will have to be employed as part of a hybrid approach, such as using CIGS for photovoltaics (to achieve high efficiencies) and amorphous silicon or organic printed active and passive devices (with some of these being embedded or integrated) for power electronics. Finally, we would like to remind that, in general, design decisions are closely related to the specifics of the application. One would need to have several customized MPPT solutions in order to meet the specific requirements of a given application. For example, stand-alone PV systems such as the ones in portable devices or wireless sensors have to consider the simplicity of the implementation (which directly affects the cost) as a primary design objective, while larger scale PV systems must take into account better power efficiencies at the expense of more complex MPPT central or distributed topologies.

Acknowledgments

The first and third authors were financially supported by the Center for Nanoscale Science and Engineering (CNSE) at North Dakota State University (NDSU). The first author was in part also supported by the Electrical and Computer Engineering Department at NDSU. The authors would like to thank the anonymous reviewers whose suggestions have strengthened the final presentation.

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Please cite this article in press as: Ababei, C. et al. Toward integrated PV panels and power electronics using printing technologies. Sol. Energy (2010), doi:10.1016/j.solener.2010.03.016

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Please cite this article in press as: Ababei, C. et al. Toward integrated PV panels and power electronics using printing technologies. Sol. Energy (2010), doi:10.1016/j.solener.2010.03.016