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Direct-DC Power System Generation Based on Single-Phase Rooftop Photovoltaic in Residential Low Voltage Feeder

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The trend of converting direct current (DC) system into alternating current (AC) using inverter becomes common since the system efficiency appropriately improves. Additionally, the mitigation on direct-DC power system requires transformer and inverters inside the appliances due to lower and convert the 230VAC into useable DC voltage. This paper proposes the direct-DC power system generation based on single-phase rooftop photovoltaic (PV) in the residential low voltage (LV) feeder. The proposed simulation designates the power system components included in the modeling of the AC and direct-DC houses, which the included power system components downstream of the PV array. The efficiency of direct-DC power supply, grid interactive inverter and charge controller are simulated. The results show that the peak curve efficiency of direct-DC power supply has DC power input narrow to 400VDC. It is then become 2% higher than 220VAC power input. While the inverter with multiple MPPT efficiency curve has the peak of 96-97% after 30% loads, while when it is partly loads, with the power capacity below 1000W, has peak at range of 86-95%. Then the efficiency curve of charge controller with MPPT for partly load scheme below 30W output power the peak is about 90-94%.

Keywords: Direct DC, rooftop PV, residential LV, inverter, MPPT.

1. INTRODUCTION

Today, the trend of converting direct current (DC) from the photovoltaic (PV) system into alternating current (AC) using inverter becomes popular since the efficiency of the system enhances appropriate. The converted voltage is distributed to the AC loads in such conventional way by using the existing building wiring in retrofit systems, supplying 240Vac to certain high power loads, such as electric high voltage alternating current (HVAC) or electric ovens and stoves, and 120Vac to low power loads [1]. Several studies have mitigated the usable DC power system to many household appliances. This implies the need for transformers and inverters inside the appliances, in order to lower the AC current of 230V and convert it to usable DC voltage. Using PV with an AC grid thus involves two energy conversions, with inherent energy losses. It is reasonable; therefore, to assume that introducing a DC LV grid can mitigate these losses [2]. In references [3,4], the observation of DC house is a promised project that can be offered as alternate solution for rural electrification and the design also has been validated as DC house power distribution system, respectively.

In the hypothetical further mitigation on direct-DC power systems with storage devices, the power would be sent directly to DC appliances, rather than first converting it to AC. That is, power distribution within the house is in DC. While such systems rarely exist at the whole home/building scales, but it is noted that some countries are emerging on this hypothesis to approach this goal, namely, Japan, Korea, and United State. The two main international actors in direct-DC have been Japan and Korea. Japan's New Energy and Industrial Technology Organization (NEDO) has modeled the potential energy savings of direct-DC and engaged Panasonic in the assessment and development of DC appliance prototypes. Korea appears to be farthest along in direct-DC research and development, having completed a large residential DC demonstration project in 2009 (a 30kW project by Samsung C&T Corp.) with DC distribution and appliances that integrates 22kW of PV, 3kW of wind power, and 200W of fuel cell capacity, along with 22kWh of battery storage.

This study claims only a modest 1.5% – 3% efficiency gain resulting from direct-DC [5]. This paper presents a concept of the direct-DC power system targeting high-energy efficiency, which overcomes the lack of

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electrification problems due to power plants issues. This high-efficiency power system concept is proposed by integrating the single-phase rooftop PVs, which have random ratings and locations in LV residential feeder. As uncertainty PVs power and placements are in the feeder, the performance of a communication-based and intelligent voltage profile regulating technique under a Monte Carlo-based stochastic framework that has been mitigated in [6] is used.

Since the system is also grid-tied connection, thus it consists of single-phase rooftop PV as the power supply, the grid interactive inverter, DC-DC converter, maximum power point tracker (MPPT) and changer controller for the battery as storage device. The overviews of those direct-DC power system components are including their typical operations, power characteristics, lifetimes and eventually the energy efficiencies.

2. LITERATURE REVIEW

In order to comprehend the energy consumptions of the proposed direct-DC power distribution systems, this section firstly provides an overview of low voltage direct current (LVDC) energy supply technologies, addresses its components and briefly finishes with the overview on the consumer' DC loads. Several studies have been conducted regarding the DC power distribution systems, further, voltage levels stands as one of the main differentiators in between proposed systems.

The system below 120 V is possible to have DC systems at those voltage levels, even with plug-in electric vehicles and kitchen loads in a house [7]. However, to do so the maximum length of the wires must be restricted and the wire gauges upgraded to AWG 6 to AWG 8 in contrast to the current AWG 12 or AWG 14 used in households. Another study that has been summarized the pros and cons of the different voltage levels (see Table 1) [8].

Table 1. Different voltage levels for different arguments

Argumentations	DC System Voltage Level (Volts)
Adaptability with existing grid of the building	$V_{DC} \geq 220$
Single-phase load adaptability	$V_{DC} \leq 238$ or 457 (phase-to phase)
Three-phase loads adaptability	$463 < V_{DC} < 617$
Efficiency (use the similar equipment)	The highest possible
Insulation	$V_{DC} \leq 373$
Component and devices matching (rated levels)	$V_{DC} \leq$ 350-450

The Differences study mentioned 48Vdc would be the optimal voltage level for residential applications based on an analysis of efficiency across a given set of case studies. In addition, for commercial applications, and applying a similar methodology, it was concluded that 400Vdc is the optimal level [9].

The fundamental concept of LVDC grid is similar with LV distribution of AC. According to reference [10] the flow of electricity through cables and components to the end-user at low voltage levels might defer in nature, characteristics or functions, therefore, the difference in between both alternatives rest on the way that the system is configured. Figure 1 illustrates the configuration of centralized direct-DC flow through the grid.

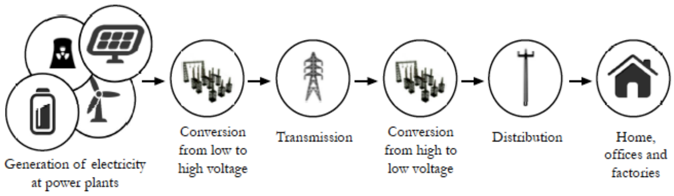

Figure 1. Grid-tied direct-DC configuration

Since this paper only mitigates the integration of PV cell system into the grid, then the focus is primarily on PVs and its relevant aspect of technology for residential and small commercial renewable energy supply. As stated in reference [1], the PV module efficiency by cell type - amorphous silicon, cadmium telluride, single crystalline, multiple crystalline, and ribbon.

The percentage of most of the models and technologies is the 11-15% range and still being produced with multiple crystalline and single crystalline silicon cells. It is also stated that both single and multiple crystalline silicon modules come with a 25-year standard guarantee and a 35-year useful life, providing the voltage at maximum power is greater than the minimum voltage required of the load. PV modules are highly resistant to damage from infrared (IR) and ultra-violet (UV) radiation, though ultimately amperage is affected by opacity in the glass, scratching, and degradation of cell material. Old PV modules may still be useful for running pumps and fans and for low-voltage battery recharging. Most PV modules now come with underground service entrance (USE-2) wire leads and multiple contact (MC) connectors for high voltage rating, UV protection, watertight connections, and abrasion resistance.

The main components that included into the direct DC grid are inverters (uni-directional and bi-directional), DC-DC converters, MPPT, charge controllers, and batteries. Grid-tie inverter, with battery backup convert DC power coming from the battery, or directly from the PV array, to AC power sent to the loads or the grid via net-metering. These devices have two important differences to their non-storage counterparts: They have a built-in rectifier to convert AC grid-power to DC required for battery charging. On the other hand, unlike most inverters without battery backup, battery backup inverters do not include MPPT, as an upstream-located charge controller performs this function.

Furthermore, the DC-DC converters are solid-state devices that convert DC power from one voltage level to another and are found in appliances with electronic circuits. The function of the DC/DC converter is to step-down the main bus voltage from 380VDC to 24VDC to supply energy for low power loads. This DC-DC converter currently does not exist specifically for residential applications, but is in the research/design stage. The MPPT is a high efficiency DC-to-DC converter that adjusts the apparent load characteristics seen by the PV array to force it to operate at maximum possible power output and produces the constant output voltage required by the load [11, 12]. Because the voltage and current supplied by the PV system depend on ambient conditions, the DC power coming from the array must be conditioned to provide appropriate power quality for the load.

MPPTs achieve this while ensuring that the PV system operates at its maximum power output for the given solar conditions. From the PV system's perspective the MPPT adjusts the apparent resistance of the loads to push it to its maximum power point. From the load's perspective, the MPPT is supplying the appropriate voltage to operate optimally. Charge controllers are used in battery back-up systems and regulate the current sent to or coming from the battery. Thus, a charge controller with MPPT performs the functions of an MPPT with the addition of current control. Batteries are the only viable choice for storage for residential and small commercial applications, given the cost of competing technologies, although flywheels have been used for short-term storage in data center applications.

Batteries are powered through a charge controller from the PV system during periods of excess PV generation and are discharged to the building loads when the grid is not available or during periods of cloud cover [13]. Many promising battery technologies are currently available including nickel-cadmium, metal-hydride and lithium-ion. However, the industry standard is lead-acid batteries, since their low capital costs and maintenance requirements. For this reason, we focus this discussion on lead-acid batteries. Direct-DC power system is delivered directly from distributed generator (DG) such as PV and battery storage unit to loads at consumers' side, rather than converting it to AC. It has been noted that mostly the loads are in AC power system mode.

Therefore, because of the different nature of loads, then in reference [14], the conceptual schematic of these loads with respect to the potential utilization of direct-DC. Specifically, the timing of these loads with respect to PV system output suggests different utilities; 1) Cooling loads, which have the maximum temporal overlap with PV system output and therefore offer the best potential for energy savings from direct-DC, and 2) Non-cooling loads, which generally is synchronous with PV output for the commercial sector and not so for the residential sector.

3. PROPOSED OF DIRECT-DC POWER SYSTEM

In this paper, there are two system that been compared, the available AC power system, and the proposed direct-DC power system with battery, respectively. The following discussions detail the power systems, the advantages and disadvantages of them are studied in this study. Thus, component of PV system are explained over subsection 3.1 until 3.3 as follows:

3.1. AC Power System with Battery

Simple schematic of AC power system with a net-metered PV system, electricity storage and variable AC/DC loads is illustrated in Figure 2. The inverter is connecting to the charge control and MPPT allowing battery charging from the solar system during the day and from the grid at night. Battery storage is essential to reach high levels of on-site PV capacity, since it needs to buffer large simultaneous peaks in local generation.

This system is very common and mostly used as the suitable renewable energy system within this century. The advantage of this power system is the infrastructure available solidly. The DG likewise PV system, wind turbine and fuel cell have possibility to attach to it. From Figure 2 can be seen that the grid-tie PV cell power output is in the range of 1-5kW, using bi-directional inverter and generates 220V household with the both vary loads as AC/DC cooling and non-cooling loads, respectively.

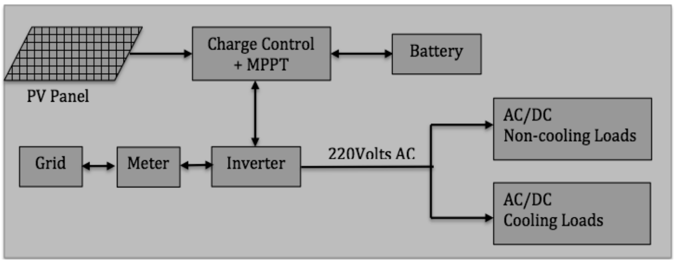

Figure 2. Schematic of AC power system with battery

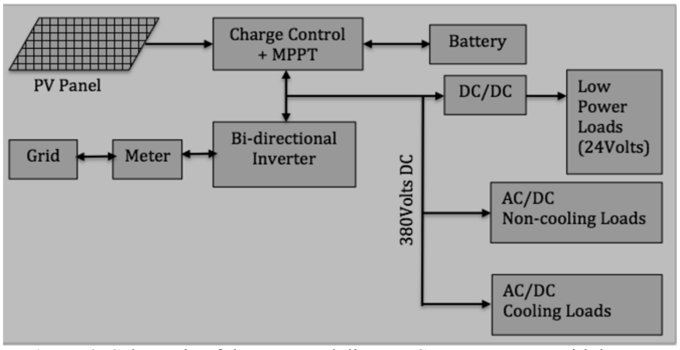

Figure 3. Schematic of the proposed direct-DC power system with battery

3.2. Direct-DC Power System with Battery

Simple schematic of proposed direct-DC power system with a net-metered PV system, electricity storage and DC load is illustrated in Figure 3. The inverter is bi-directional, allowing battery charging from the solar system during the day and from the grid at night. The loads in the system are the same as in AC power system, except for the AC/DC power supplies. Power is distributed at 380VDC for high power loads and at 24VDC for low power loads. As mentioned earlier, In the direct-DC, power from DC power systems or storage devices would be sent directly to DC appliances, rather than first converting it to AC. That is, power distribution within the house is in DC form.

This approach excludes the usual DC-AC-DC conversion losses experienced in powering DC-internal loads (as adequate PV power is available to supply them). However it experiences other losses since AC grid backup power must now be converted to DC when PV power is not sufficient to power loads and any excess DC power must now be inverted to AC for net metering. The PV array still needs a maximum power point tracker, which provides the necessary constant voltage to the load and adjusts the apparent load characteristics seen by the PV array to force it to operate at maximum power output. MPPT is typically built into today's PV-system inverters. Additionally, a DC-DC converter, or possibly multiple ones, would be needed to convert the high voltage DC coming from the array and going to high power loads to lower power loads that operate at lower voltage.

Table 2. Power characteristic and lifetime of direct-DC power system components

Components	Power Characteristic	Lifetime
Inverter with battery back up	- Battery back up 24/48 VDC - Anti-islanding - Continue invert power either PV or battery in critical loads - Similar to uninterruptible power supply (UPS)	- 2 years standard warranty - Extended 5 years warranty on its model
DC-DC Converter	- For residential produce low power - For DC building produce 1-5kW	- 2-3 years warranty - Some claims to 10 years warranty
MPPT	- Input voltage range 12 VDC in small charge controllers - Input voltage range 600 VDC in grid-tie inverters	- 20-25 years warranty
Charge controller	Operating range 4.5-80 A	- 16-25 years warranty
Battery	- Lead-acid battery nominal voltage 2V wired in series, - Applied for PV at 12V, 24V, and 48V - Temperature 75°F	- 5-10 years warranty, approximately 390 Ah - 15-20 years warranty, approximately 1600 AH

3.3. Direct-DC Power System Battery Configuration

The system configuration identifying the maximum charging capacity of battery is 5kWh, and the minimum is 1kWh. Table 2 summarizes the power characteristics and lifetime of the mentioned components. Moreover, the battery efficiency is assumed to be 90% in one-way and 81% in round-trip as shown in Table 3.

Table 3. Battery efficiency towards the power system components

Power system components	Model efficiency	Component efficiencies
PV Inverter (AC house) includes MPPT	95%	Typical of today's new PV-system storing inverter
DC-house rectifier (meter to DC)	93%	Represents best models that could be built today, according to industrial experts
DC-house inverter (DC to meter)	97%	Today's PV system inverter no MPPT estimated losses 2%
Charge controller or MPPT	98%	Typical of today's high-end charge controller efficiency
DC-house DC-DC converter 380-24V	95%	Represents best models that could be built today, according to industrial experts
Battery (one-way)	90%	Varies depends on storage and state of charge

Table 4. Load efficiencies toward the power system components.

Power system component	Full-load efficiency	Part-load efficiency
AC-house inverter, includes MMPT	95%	90%
DC-house rectifier (meter to DC)	93%	84%
DC-house inverter (DC to meter)	97%	92%
Charge controller MPPT	98%	94%
DC-DC converter: 380 to 24V	95%	87%

Table 5. Comparison of loss reduction to implement saved direct-DC

	Cooling load	Conversion reduction	Storage direct-DC savings
AC House	AC/DC power supply	10% less to 7%	12.8% less to 9.3%
	Non-cooling load AC/DC power supply	13% less to 10%	
DC House	DC/DC converter (380/24V)	5% less to 3%	12.8 become 13.7%
	Rectifier (AC/DC)	7% less to 5%	

4. RESULTS AND DISCUSSION

Since the energy impacts of using direct-DC versus AC appliances lounge not only in the differences between the appliance, but also in the difference between the AC versus direct-DC power systems connecting the appliances, PV system, and grid—appliance-level savings tell only a part of the story. To determine the net energy savings, the product-level characteristics were input to an AC- versus direct-DC-house energy use model [1]. More specifically, to distinguish the impact of direct-DC- versus AC-distribution, two sets of appliances for the modeling work were defined.

These appliances were identical in every way other than their front-end power interface. The direct-DC-appliance establishes the basis set. The AC appliance is just the DC-appliance with an AC-DC converter on the power input. Firstly, we determine the availability of direct-DC-based technologies to serve 30 residential end-uses and estimate the energy implications of switching from standard technologies to the most efficient direct-DC-based technologies, assuming that both the standard appliance and its DC-internal counterpart is running on AC. Then, we estimate energy savings at the appliance level resulting from the avoided AC-DC conversion losses in the DC appliances.

Let us consider that the battery appear in every residential. In none of the residential are batteries at minimum or maximum capacity for undue period of time. In addition, battery is appeared highly active, receiving a high percentage of excess PV power and serving high percentage of loads. Thus, all houses with storage system achieve their primary goal, which is to minimize power coming from grid and buffering power sent to grid.

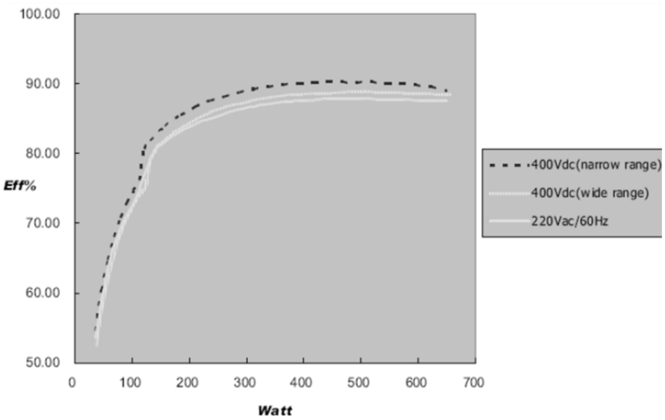

Figure 4. Direct-DC power supply efficiency

As can be seen in Figure 4, the efficiency of direct-DC power supply, grid interactive inverter and charge controller while the peak curve efficiency of direct-DC power supply has DC power input narrow to 400VDC then become 2% higher than 220VAC power input (see Figure 5).

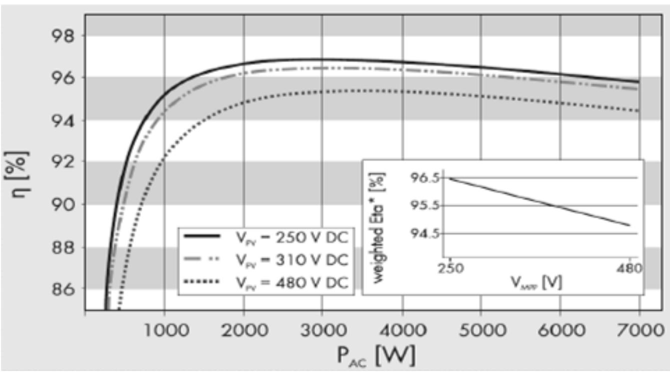

Figure 5. Grid interactive inverter efficiency

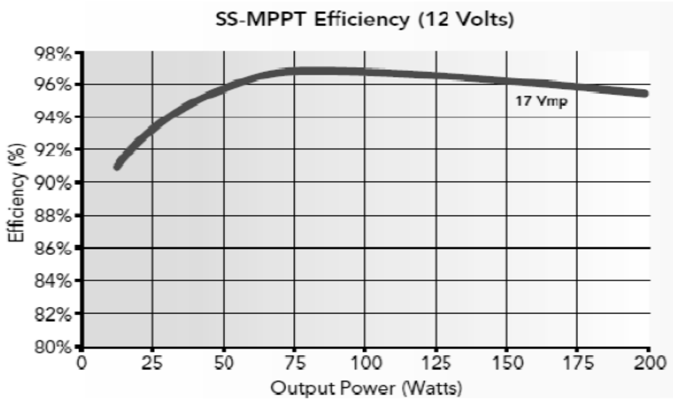

Figure 6. Charge controller efficeincy

Furthermore, Figure. 6 shows the inverter with multiple MPPT efficiency curve has the peak of 96-97% after 30% loads, while when it is partly loads, with the power capacity below 1000W, has peak at range of 86-95%. Then the efficiency curve of charge controller with MPPT for partly load scheme below 30W output power the peak is about 90-94%. The simulation designates the power system components included in the modeling of the AC and direct-DC houses as can be seen in Figure 2 and 3, respectively, all power system components downstream of the PV array. Each entry indicates whether the component is used for the AC or the direct-DC house. It aims to explain the energy efficiency assumptions used in the modeling and certain decisions about component configurations. The modeling simulates efficiencies that represent the high end of the current. Since the direct-DC-house power system is hypothetical, the assumed characteristics of its components. From full- and part-loads' point of view, regarding to the power system components, the efficiencies are described in Table 4. In addition, Table 5 shows the comparison of AC and DC houses regarding their loss reduction and the implementation to the direct-DC saving issues.

5. CONCLUSIONS

The direct-DC power system generation, which based on single-phase rooftop PV in the residential LV feeder, has been proposed. Several major findings can be concluded as follow; essentially all end-uses are DC compatible, the switching to DC internal appliance saved approximately 33%, whether they run on AC or DC. Direct-DC could save energy in net-metered houses with PV, which has best estimate approximately 13% as the storage limits applied. For all configurations, the relative power system and appliance conversion efficiencies have the most significant effect on the direct-DC savings. If improvements in appliance conversions efficiencies (power supplies) improve faster than power system component efficiencies, the relative benefits of direct-DC over AC are going down.

Moreover, future trends in system component efficiencies are not likely to significantly affect the relative benefits of DC over AC, since some of these improvements favor AC distribution while others favor DC distribution. Such improvements do of course reduce overall energy use.

References

1. K Garbesi, V Vossos, and H Shen, "Catalog of DC Appliances and Power Systems," Energy Analysis Department Environmental Energy Technologies Division Lawrence Berkeley National Laboratory, Berkeley,**(2011)**CA 94720,.
2. M M Friedeman, E C Boelman, A van Timmeren, and J Schoonman, "Concept for a DC low voltage house," presented at Sustainable Building conference, (**2002**) Paper_SB02_#217.doc.
3. T Taufik, "The DC House Project: An Alternate Solution for Rural Electrification," presented at IEEE 2014 Global Humanitarian Technology Conference, (**2014)** 978-1-4799-719 3-0/14 IEEE.
4. J Crowfoot, "*Design and Modeling of the Cal Poly DC House Power Distribution System*," a master thesis of Science in Electrical Engineering that presented to the Faculty of California Polytechnic State University, (**2011)** San Luis Obispo,.
5. J Baek, S Gab-Su, C Kyusik, P Cheol-Woo, K Hyejin, B Hyunsu, & H C Bo, *DC Distribution system design and implementation for Green Building*, in *Green Building Power Forum* (**2011)**: San Jose, CA.
6. N Safitri, F Shahnia, and M A S Masoum, "*Monte Carlo-based Stochastic Analysis Results for Coordination of Single-Phase Rooftop PVs in Low Voltage Residential Networks*," Intelligent Industrial System Journal, **(2015)** 1:359–371, DOI 10.1007/s40903-015-0029-2, © Springer Science + Business Media Singapore,
7. W Li, X Mou, Y Zhou, and C Marnay, "On voltage standards for DC home microgrids energized by distributed sources," presented in Power Electronics and Motion Control Conference, (**2012**)pages 2282–2286,. ISBN 9781457720888.
8. H Pang, B Pong, and E W C Lo, "A practical and efficient DC distribution system for commercial and residential applications 240 V or higher," presented at the international conference on electrical engineering (**2008**), pages 1–4,.
9. M A Vargas Evants, "Why Low Voltage Direct Current Grids? A case-study assessment of using direct current in low voltage distribution," a master thesis of science in Sustainable Energy Technology, Delft University of Technology, (**2013**).
10. S Anand, and B G G Fernandes. Optimal voltage level for DC microgrids. IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society, (**2010)**, pages 3034–3039,.
11. F C Lee, et al., *Proposal for a MiniConsortium on Sustainable Buildings and Nanogrids*, Center for Power Electronic Systems, Virgina Tech: Blacksburg, VA, (**2010)**.
12. Nextek Power Systems. *Technical Document Library*. Available from: http://www.nextekpower.com/technology/technical-document-library.
13. AEE Solar. *2010 Renewable Energy Design Guide and Catalog*. **(2010),** Available from: http://www.aeesolar.com/PDFs/aee-solar-2010-catalog.pdf.
14. EMerge Alliance. *An open industry association. (***2011)**, Available from: http://emergealliance.org.

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