Quantification of Losses in a Photovoltaic System: A Review [†]

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Abstract: In this paper, we characterized and reviewed the emergence of fundamental and extended losses that limit the efficiency of a photovoltaic (PV) system. Although there is an upper theoretical bound to the power conversion efficiency of solar cells, i.e., the Shockley Queisser limit, in a practical environment, the consideration of inevitable losses in a whole PV system is imperative to optimally harvest solar energy. In this regard, this study quantifies the losses from a PV cell level to the whole PV system. It was perceived that reported losses on the PV cell level included the low energy bandgap, thermalization, recombination (surface and bulk recombination), optical absorption, space charge region, finite thickness, and metal contact loss, and it was determined that cutting techniques mainly constrained the power conversion efficiency of the solar cell. Furthermore, the detailed PV array losses were classified as mismatch power losses, dust accumulation losses, temperature effects, material quality losses, and ohmic wiring losses. The unavoidable system losses were quantified as inverter losses, maximum power point tracking losses, battery losses, and polarization losses. The study also provides insights into potential approaches to combat these losses and can become a useful guide to better visualize the overall phenomenology of a PV System.

Keywords: PV cell; PV modules; losses; quantification

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1. Introduction

In the last few years, photovoltaics (PV) have emerged as a pioneer technology to meet the energy demands of small-scale consumers to those of the commercial sector and provide a cost-beneficial solar power generation system that can be used to offset the electricity costs from utility providers as well as alleviate the burden on the national electricity grid. Another major advantage of PV systems is the emission reduction benefits [1,2]. Presently, the installed PV capacity is around 109 GW_p, and this could cross 149 GW_p by 2022 according to the International Energy Agency (IEA), France [3]. This trend certainly demonstrates unparalleled progress in efficiency enhancement in the area of photovoltaics combined with power electronic-aided hybrid converters as well as cutting edge cost benefits, yet the emergence of losses in real environmental conditions is inevitable, as these losses cannot be eliminated beyond fundamental limits [4–6].

PV cells harvest solar energy to yield photogenerated power. The performance of solar cells depends on the available solar insolation and the spectral distribution of incident wavelengths over the surface of the PV system. The output of the solar cell is generally measured in standard testing conditions (STC); irradiance 1000 W/m², temperature 25 °C, and standard earth spectrum AM 1.5 G, where G stands for global and includes both direct and diffuse radiation [7–9]. The solar cell performance is characterized based on parameters including open-circuit voltage (V_{oc}), the voltage at the maximum power point (V_{mp}), the short circuit current (I_{sc}), current at the maximum power point (I_{mp}), and the maximum power point (P_{mp}), which can be extracted from the current–voltage (I–V) characteristics

shown in Figure 1 [5]. The efficiency (η) of the solar cell is the ratio of available solar energy to the converted electrical energy, which can be calculated using the percentage of the maximum power point and the surface area of the solar cell (A) into irradiance (I_r), which is provided by Equation (1).

$$\eta = \frac{P_{mp}}{A \times I_r} (\%) \quad (1)$$

Figure 1. Generic current–voltage (I–V) and power–voltage (P–V) characteristics of a photovoltaic cell [5].

In real environmental conditions, several factors affect the performance of PV cells. Herein, we first reviewed the major losses from PV cells to the overall PV system and subsequently characterized and presented the losses in a pictorial form for better visualization and understanding for the reader.

2. Quantification of Losses in a Photovoltaic System

2.1. Losses in a Photovoltaic Cell

The loss mechanisms in a PV cell are initiated by the fundamental inability of the solar absorber-layer material (silicon, gallium arsenide, perovskite, copper indium gallium selenide (CIGS), among others) to potentially absorb all incident light wavelengths [10]. Incident light wavelengths with a photon energy (E_{ph}) less than the energy bandgap (E_g) of the absorber layer are unable to be absorbed. Such losses are the *below energy band gap losses* and are shown mathematically by Equation (2) [11].

$$\text{Below } E_g \text{ Loss} = \int_0^{E_g} E \cdot GP(E, \Omega_A, T_S, \mu = 0) dE \quad (2)$$

The photons with energy $E_{ph} > E_g$ generate electron–hole pairs. However, the carriers with high kinetic energy sometimes decay to the band edges quickly from their initial excited states to reach their thermal equilibrium states, releasing their excess energy upon interaction with the crystal lattice. Such losses can be categorized under *thermalization loss*, and the mathematical relationship is given in Equation (3) [12–14].

$$\text{Thermalization loss} = \frac{E_g \int_0^{\lambda_g} \Phi(\lambda) d\lambda}{\int_0^{\lambda_g} \Phi(\lambda) \frac{hc}{\lambda} d\lambda} \quad (3)$$

Thermodynamic studies on a PV cell demonstrated that at temperature > 0 K, a voltage drop is associated with the PV cell, which is termed as *etendue loss* [15]. Moreover, *Fermi level losses*; losses associated with the displacement of the V_{oc} and E_g relationship and

electron kinetic losses; and losses underlying the inefficacious use of the carriers' kinetic energy during the thermalization process are among the major thermodynamic losses that limit the efficiency of solar cells [14–16]. Besides this, operating solar cells at P_{mp} could also result in reduced output performance because of series and shunt resistance effects and is referred to as *fill factor loss* [17].

In practical scenarios, part of the incident light that falls on the surface of a solar cell is reflected or transmitted instead of being absorbed. Such losses are referred to as *optical losses* [18]. The reflected portion of the incident light is also separately named the *reflection loss* [13,18]. The reflection losses directly reduce the I_{sc} of solar cells. Similarly, the finite thickness or geometry of the solar cell contributes to *transmission losses* in a PV cell [13,18]. In a wafer-based solar cell, the part of the cell that makes contact with the front side of the cell (from where light enters) is made of a finger and bus bar. These metal contacts shadow some light, which can be up to 10% [16–18]. Such losses tend to create *area losses/losses due to metal coverage*.

The photons on the solar cell generate electron–hole pairs, and these generated carriers need to be separated in order to reach their respective metal contacts before they recombine. The recombination of the carriers can be attributed to *recombination losses* in a solar cell. Recombination losses can be further classified as (i) surface recombination; (ii) bulk recombination; (iii) depletion region recombination; and (iv) recombination at the metal contacts [19].

2.2. Photovoltaic Array Losses

Under same environmental conditions/STC, identical PV cell/module/arrays sometimes exhibit un-identical P_{mp} values because of manufacturing errors that can be attributed as *mismatch power loss* [20]. It is to be noted that under heterogeneous irradiation conditions (partial shading), mismatch power loss is modeled separately due to variation in the module performance/physical environments.

The accumulation of dust over the surface of the PV module results in reduced photogenerated power and also affects the angle of incidence reaching the absorber layer of the solar cell. Such losses are referred to as *dust accumulation losses* [21]. Besides these varied irradiance values that accumulate over time, irradiance losses and temperature impacts (hot spot issues), temperature losses, and DC wiring ohmic losses seriously affect the power conversion efficiency of PV modules [22,23].

2.3. System-Level Losses

On a system level, the *inverter losses*, *batter losses*, *maximum power point tracking (MPPT) topology losses*, and potential-induced degradation or polarization losses are among the major types of PV system losses that result in reduced PV system performance over time [24,25].

For better understanding, the above-mentioned PV cell system losses have been shown pictorially in Figure 2.

Figure 2. Characterization of losses in a photovoltaic system: cell to system level.

3. Possible Ways to Combat Losses

3.1. Addressing Photovoltaic Cell-Level Losses

The *below energy band gap*, *thermalization*, *Fermi level losses*, and *etendue losses* can be addressed by employing an absorber layer material with low E_g or multi-junction approaches. In emerging PV technology, tuning the energy bandgap of organic/inorganic absorber layer properties can be useful to combat the above-mentioned issues. The *optical* and *reflection losses* can be addressed by using surface texturing and anti-reflective coatings (the material should have good transmittance). The *transmission losses* can be addressed by employing an appropriate wafer geometry and thickness to absorb the maximum amount of incident light wavelengths. The *area losses* can be mitigated by reducing the widths of the finger over the top surface while expanding the contact size of the back metal. The *surface recombination losses* can be reduced by passivating the surface to reduce dangling bonds or by adopting a window layer to limit the path of the minority charge carriers at the maximum amount. *Depletion region recombination losses* are not the most prominent type of loss. *Bulk recombination losses* can be addressed by using a pure semi-conductor material while rear surface passivation approaches could aid in combating metal contact recombination sites [11–19].

3.2. Addressing Photovoltaic Array Losses

The *mismatch power losses* can be addressed via the application of by-pass/blocking diodes or cell-cutting approaches. The *dust accumulation losses* can be addressed by properly cleaning the PV module with demineralized water or with an electro-static cleaning system. The *temperature losses* can be addressed by considering appropriate module technology (crystalline, crystalline PERC, thin-film), while DC wiring losses can be mitigated by using wires with good conductance and a minimum number of connections [20–25].

3.3. System-Level Losses

With the employment of efficient power electronic-aided topologies, inverter, MPPT, and polarization losses can be addressed [25,26]. Proper battery sizing, advancement towards dry batteries rather than lead–acid Batteries, and moderate temperature, battery dispatch strategies can aid in mitigating *battery losses* in PV systems [27].

4. Conclusions

Depending on the nature of the losses experienced in a PV system reported in the literature, we broadly and briefly classified the major types of losses that are responsible for the reduced efficacy of whole PV systems at the PV cell level, array level, and system level and presented them in a pictorial form. Further, we discussed potential solutions to overcome fundamental and extended losses in PV systems. This illustration may become a brief and useful guide to create awareness of issues that may occur at the PV cell fabrication level and how they affect the whole PV system.

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