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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 the photovoltaic (PV) system. Although in a practical environment, there is an upper theoretical bound to the power conversion efficiency of the solar cell i.e. Schockly Queisser limit yet the consideration of inevitable losses in a whole PV system is worth imperative to optimally harvest the 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 a PV cell level including the low energy bandgap, thermalization, recombination (surface and bulk recombination), optical absorption, space charge region, finite thickness, metal contact loss, cutting techniques mainly constrained the power conversion efficiency of the solar cell. A step ahead, the detailed PV array losses were classified as mismatch power loss, dust accumulation losses, temperature effects, material quality loss, and ohmic loss of wiring. The unavoidable system losses were quantified as inverter losses, maximum power point tracking losses, battery losses, and polarization losses. The study also provides insights on potential approaches to combat these losses and can become a useful guide in better visualization of 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, photovoltaic (PV) emerged as pioneer technology to meet-up energy demands from small scale consumer to the commercial sector and provides a cost-beneficial solar power generation system that can be used to offset the electricity cost from utility provider 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 would cross 149 GW_p by 2022 according to 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 losses emergence in real environmental conditions are inevitable as the losses cannot be eliminated beyond the fundamental limits [4-6].

PV cell harvest solar energy to yield photogenerated power. The performance of the solar cell depends upon 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 at standard testing conditions (STC); Irradiance 1000 W/m^2, Temperature 25

℃ and standard earth spectrum AM 1.5 G where G stands for global and includes both direct and diffuse radiation[7]. The performance of the solar cell is characterized based on the parameters including; open circuit voltage (V_{oc}), voltage at the maximum power point (V_{mp}), 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) [8,9]. The efficiency (η) of the solar cell is the ratio of available solar energy to the converted electrical energy which can be calculated by having the percentage of maximum power point and the surface area of the solar cell (A) into irradiance (I_r) given by (1) .

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

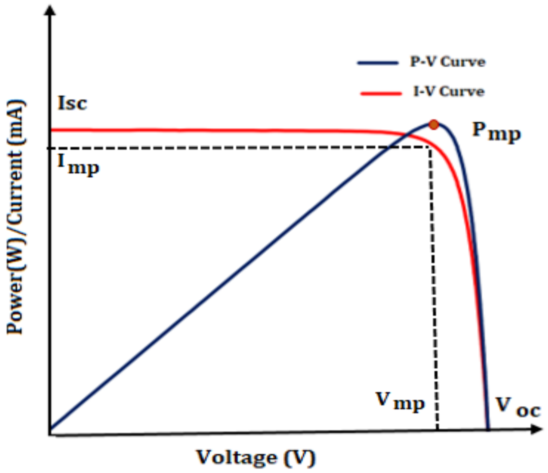

Figure 1. Generic Current-Voltage (I-V) and Power-Voltage (P-V)characteristics of a photovoltaic cell [5]

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

2. Quantification of losses in a Photovoltaic System

2.1. Losses in a Photovoltaic Cell

The loss mechanisms in a PV cell initiates with the fundamental inability of solar absorber-layer material (Silicon, Gallium Arsenide, Perovskite, Copper indium Gallisum selenide CIGS and others) to potentially absorb all incident light wavelengths [10]. Incident light wavelengths with photon energy (E_{ph}) less than energy bandgap (E_g) of the absorber layer not get absorbed. Such losses are the *Below Energy Band Gap Losses* and mathematically given by (2) [11].

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

The photons with energy$E_{ph} > E_g$ generate electron-hole pairs. However, the carriers having high Kinetic Energy sometimes decay to the band edges quickly from their initial excited states to reach thermal equilibrium states releasing their excess energy on interaction with the crystal lattice. Such losses come under *Thermalization loss and* the mathematical relation is given in (3) [12-14].

$$Thermalization\ \ loss = \frac{Eg\ \ \int_0^{\lambda g} \Phi(\lambda)\, d\lambda}{\int_0^{\lambda g} \Phi(\lambda) \frac{hc}{\lambda}\, d\lambda} \tag{3}$$

Thermodynamic studies on a PV cell demonstrated that at temperature > 0 K, a voltage drop is associated with the PV cell termed as *Etendue loss* [15]. Moreover, *Fermi level losses;* losses associated with displacement of V_{oc} and and E_g relation and *Electron Kinetic losses;* losses underlying the inefficacious use of kinetic energy of carriers during the thermalization process are among the major thermodynamic losses that limit the efficiency of the solar cells [14-16]. Besides this, operating solar cells at P_{mp} could also results 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 incident light falling on the surface of the solar cell gets 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 as the *Reflection loss* [13,18]. The reflection losses directly reduced the I_{sc} of the solar cell. 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 contact to the front side of the cell (from where light enters) is made from a finger and bus bar. These metal contacts shadow some light which can be up to 10% [16-18]. Such losses tend to originate *Area losses/losses due to Metal Coverage*.

Photons incident on the solar cell generates electron-hole pairs and these generated carriers need to be separated to reach the respective metal contacts before they recombine, . The recombination of the carriers attributes to *Recombination losses* in a solar cell. Recombination losses are 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

The identical PV cell / module/ array under same environmental conditions/ STC some times exhibit un-identical P_{mp} values because of manufacturing errors which is 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 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 incidence reaching the absorber layer of the solar cell. Such losses are referred to as *Dust Accumulation losses* [21]. Besides this varied irradiance values over time; Irradiance Losses, and temperature impacts (hot spot issues); Temperature Losses, and DC wiring Ohmic losses seriously affect the power conversion efficiency of the PV module [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 PV system losses that result in reduced performance of the PV system over time [24, 25].

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

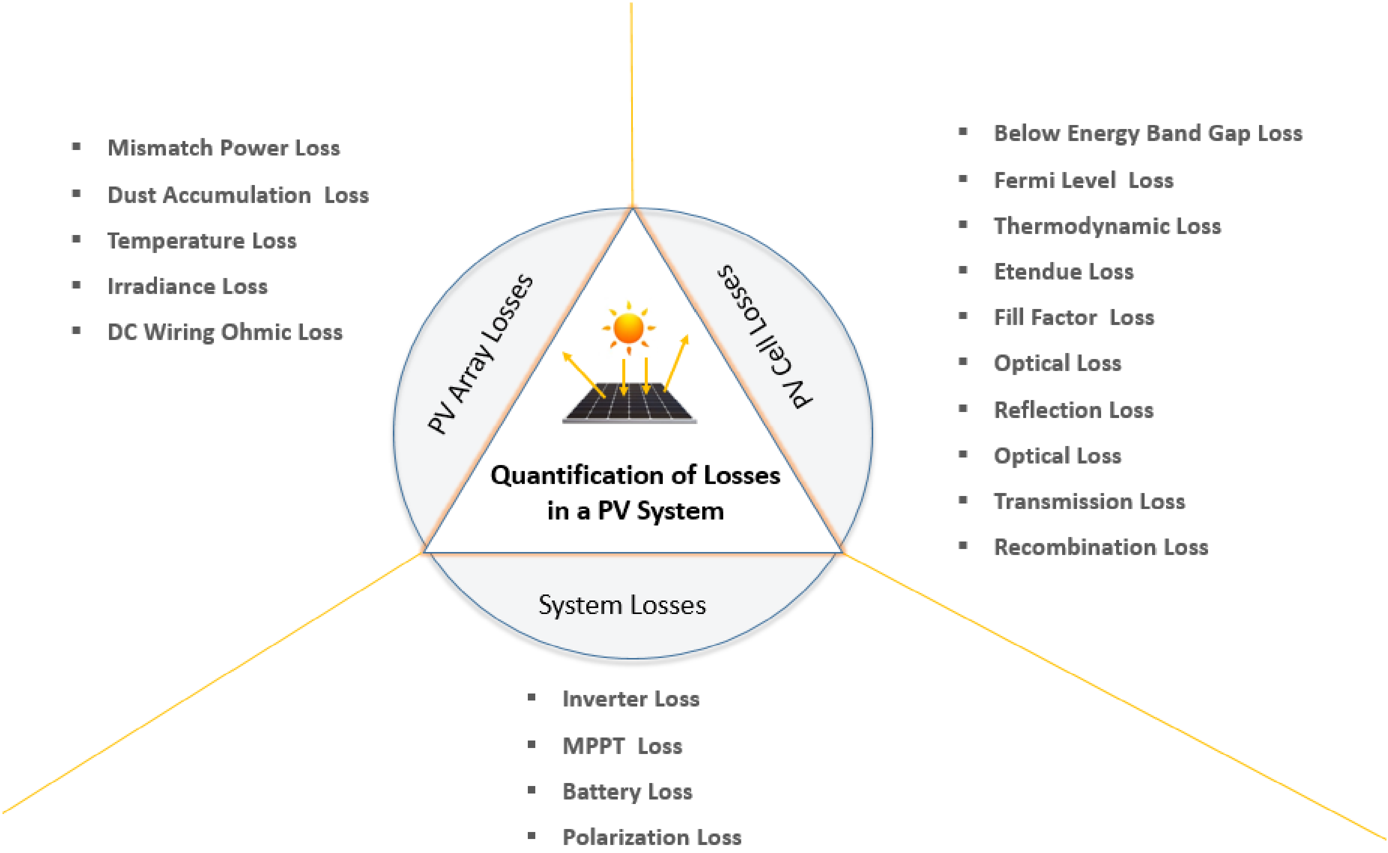

Figure 2. Characterization of Losses in a photovoltaic systems; cell to system level

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 absorber layer material of low E_g or multi-junction approaches. In emerging PV technology, energy bandgap tuning 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-reflecting coatings (the material should have good transmittance). The *Transmission losses* can be addressed by employing appropriate wafer geometry and thickness to absorb maximum incident light wavelengths. The *Area Losses* can be mitigated by reducing the widths of the finger over the top surface while expanding back metal contact size. *Surface recombination losses* can be reduced by passivating the surface to reduce dangling bonds or adopting of window layer to limit the path of minority charge carriers at a maximum. *Depletion region recombination losses* is not the most prominent. *Bulk recombination losses* can be addressed using 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 by the application of by-pass/blocking diodes or cell-cutting approaches. The *Dust accumulation losses* can be addressed by proper cleaning of PV module with demineralized water or 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 of good conductance and a minimum number of connections [20-25].

3.3. System-Level Losses

With the employment efficient power electronics aided topologies, Inverter, MPPT, and Polarization losses can be addressed [25, 26]. Proper sizing of Battery, advancement towards Dry batteries rather than Lead –Acid Batteries and moderate temperature, battery dispatch strategies can aid in mitigating *Battery Losses* in the PV System [27].

4. Conclusion

Depending upon the nature of losses in a PV system reported in the literature, we broadly and briefly classified major losses responsible for reduced efficacy of the whole PV system as; PV cell level, array level, and system-level and presented them in a pictorial form. Further, we discussed the potential solutions to overcome fundamental and extended losses in the PV system. This illustration can become a brief-useful guide in getting aware of the PV-cell fabrication level issues to the whole PV system.

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Conflicts of Interest: The authors declare no conflict of interest.

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