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Impact of high-voltage power transmission lines on photovoltaic power production

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ABSTRACT

One important issue not reported in the literature is to determine the impact of a high-voltage (HV) power transmission line on the power production of a photovoltaic (PV) module located near the power transmission line. Since grid-connected PV power generation systems are generally located near HV power transmission lines, this issue becomes even more crucial. For the first time, this research work addresses this issue by presenting a novel comprehensive theoretical analysis and providing relevant experimental verifications. The outcome of this study demonstrates that the electric field of the electromagnetic (EM) wave produced by a HV power transmission line has no influence on the output power of a PV module located near the power transmission line, while the magnetic field of the EM wave has a huge negative impact on the output power. Moreover, this impact intensifies when the current of the power transmission line becomes larger to respond load demand, and declines by increasing the distance between the PV module and the conductors of the power transmission line. Finally, to high efficiently utilize PV power generation systems, a minimum distance of 200 m between PV panels and HV power transmission lines is recommended.

1. Introduction

Because of environmental issues and economic considerations, there is an upward trend in developing the usage of solar energy, so that, there is an ascending demand for stand-alone and grid-connected PV power generation systems (Fathabadi, 2017a, b). As a result, there is currently a highly concentrated attempt to enhance the power efficiency of PV cells (Liu et al., 2017). Modifying the materials currently used in PV cells to enhance their performance has been the subject of many researches, for instance, adding indium and potassium fluoride to the basic materials of a PV cell to improve its performance (Zhang et al., 2017; Khatri et al., 2017). Taking suitable peripheral elements or devices into account to improve the PV efficiency is another topic addressed by many research works, for instance, implementing maximum power point trackers (Rezk and Eltamaly, 2015; Fathabadi, 2016a, b), and utilizing high-power matching device (Fathabadi, 2017c). Analyzing the effect of the environmental parameters such as temperature on the performance of a PV cell is the third topic that has attracted many attentions (Elbreki et al., 2017). Concerning the third item, a through survey of the current literature demonstrates that the effect of almost all the environmental factors such as wind (Kaldellis et al., 2014), dust (Mou et al., 2016; Paudyal and Shakya, 2016; Tanesab et al., 2017), mud (Yilbas et al., 2017) and even thermal insulation of the back side of PV modules (Koehl et al., 2016) has been analyzed and reported. The survey also shows that there is not any research, technical report, or even a trivial comment available in instruction manuals regarding the effect of a HV power transmission line on the *P-V* characteristic of a PV module located near the power transmission line. This issue is extremely important because grid-connected PV power generation systems are usually sited near HV power transmission lines. For the first time, this paper addresses this issue by presenting not only a novel comprehensive theoretical analysis but also related experimental verifications. The rest of this paper is organized as follows. Novel theoretical analysis regarding the impact of external electric and magnetic fields on a silicon PV cell by taking into account the behavior of its p-n junction is presented in detail in Section 2. As other part of the theoretical basis of this paper, novel analysis of interaction between the EM wave produced by a HV power transmission line and light wave is given in Section 3. Experimental verifications are given in Section 4, and the paper is concluded in Section 5.

2. Evaluating the influence of external electric and magnetic fields on a silicon PV cell

The structure of a silicon PV cell is shown in detail in Fig. 1. In the p-n junction of the PV cell, electrons which are majority carrier in the emitter (n-type semiconductor) move from the emitter towards the base (p-type semiconductor), so positive ion cores appear in the emitter.

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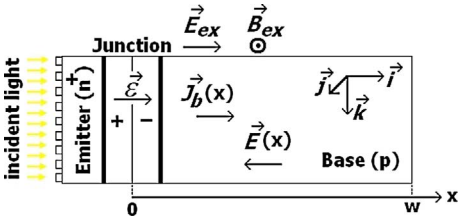

Fig. 1. Structure of a silicon PV cell.

Similarly, holes which are majority carrier in the base move from the base towards the emitter, so negative ion cores occur in the base. The two exposed ionic areas form a depletion region, and produce an electron field ($\vec{\varepsilon}$) at the junction ($x = 0$) called "junction electric field" that its direction is from the emitter to the base as shown in Fig. 1. Irradiating the PV cell by light generates electron-hole pairs when energy of the incident photon becomes more than that of the band gap energy. Electrons in the base, and holes in the emitter are meta-stable and exist for a length of time called "minority carrier lifetime" before they recombine. But, if a light-generated minority carrier reaches the p-n junction, it is immediately swept across the junction by the junction electric field ($\vec{\varepsilon}$), and participates in production of photocurrent. Collecting light-generated minority carriers by the p-n junction causes a movement of electrons to the emitter and holes to the base, so the photocurrent is produced at the p-n junction where $x = 0$. The photocurrent density in the base does not remain constant, and decreases along the base because of electron-hole recombination, so the photocurrent density in the base is a function of the distance from the junction (x), and is represented by $\vec{J_b}(x)$ in Fig. 1. The relationship between the magnitudes of the junction electric field and photocurrent density at the junction ($x = 0$) is expressed as (Fahrenbruch and Bube, 1983):

$$|\vec{\varepsilon}| = \frac{|\vec{J_b}(0)|}{q(n\mu_n + p\mu_p)} \tag{1}$$

where n is the density of light-generated electrons in the base, μ_n is the electron's mobility, p is the density of light-generated holes in the emitter, μ_p is the hole's mobility, and q is the elementary charge, i.e., $q = 1.602 \times 10^{-19}$C. The photocurrent density at the junction is obtained from Eq. (1) as:

$$|\vec{J_b}(0)| = q(n\mu_n + p\mu_p)|\vec{\varepsilon}| \tag{2}$$

Applying an external electric field ($\vec{E_{ex}}$) in the direction of the junction electric field such as that shown in Fig. 1 modifies Eq. (2) as:

$$|\vec{J_b}(0)| = q(n\mu_n + p\mu_p)(|\vec{\varepsilon}| + |\vec{E_{ex}}|) \tag{3}$$

Thus, the photocurrent density increases that results in enhancing the power production of the PV cell too. Similarly, the photocurrent density, and hence, PV power decreases when the external electric field points in the direction opposite to the junction electric field because in this case the photocurrent density at the junction is obtained as:

$$|\vec{J_b}(0)| = q(n\mu_n + p\mu_p)(|\vec{\varepsilon}| - |\vec{E_{ex}}|) \tag{4}$$

An external alternating electric field originating from an AC voltage such as that produced by a HV power transmission line is sinusoidal. At positive half cycle it points in the direction of the junction electric field, while at negative half cycle it points in the opposite direction. This means that an external alternating electric field has no impact on the photocurrent density, and therefore, on the PV cell's output power because the photocurrent density over one complete cycle is found using Eq. (3) as:

$$\begin{aligned}|\vec{J_b}(0)| &= \int_0^T q(n\mu_n + p\mu_p)[|\vec{\varepsilon}| + E_m\sin(\omega t)]dt = q(n\mu_n + p\mu_p)|\vec{\varepsilon}|\\ &\quad + q(n\mu_n + p\mu_p)\int_0^T E_m\sin(\omega t)dt = q(n\mu_n + p\mu_p)|\vec{\varepsilon}|\end{aligned} \tag{5}$$

where E_m and ω are respectively the magnitude and angular frequency of the of the external alternating electric field. Eq. (5) explicitly demonstrates that the photocurrent density, and as a consequence, the PV power production does not depends on the external alternating electric field. Thus, it is concluded that an external alternating electric field has no impact on the power production of a PV cell as well as a PV module.

By applying an external magnetic field to a PV cell like that shown in Fig. 1, the minority carriers (electrons) coming from the base towards the p-n junction deviate from their path, and a reduction in their effective mobility occurs. Similarly, the minority carriers (holes) coming from the emitter towards the junction deviate from their trajectory that results in a reduction in their effective mobility. In Fig. 1, the electrons in the base, and the holes in the emitter turn to, respectively, up and down. When an external alternating magnetic field such as that produced by a HV power transmission is applied, the only difference is that the electrons in the base turn to up at positive half cycle, and turn to down at negative half cycle. Under this condition, the holes in the emitter turn to the direction opposite to that of the electrons in the base. Thus, the impact of an alternating magnetic field on the PV cell is similar to that of a constant magnetic field. They both decrease the output power of the PV cell by reducing the effective mobility of the minority carriers participating in photocurrent production. This point can be also formulized as follows. The photocurrent density in the base is expressed by using the transportation phenomena equation as (Betser et al., 1995):

$$\vec{J_b}(x) = qD_n\vec{\nabla}\delta(x) + q\mu_n\delta(x)\vec{E}(x) \tag{6}$$

where D_n is the electron's diffusion coefficient, $\delta(x)$ is the excess minority carrier density in the base, and $\vec{E}(x)$ is the electric field originating from carrier concentration gradient along the base that its magnitude is given as (Pelanchon et al., 1992):

$$|\vec{E}(x)| = \frac{D_p - D_n}{\mu_p + \mu_n}\frac{1}{\delta(x)}\frac{d\delta(x)}{dx} \tag{7}$$

In Fig. 1, in absence of the external magnetic field ($\vec{B_{ex}}$), there is no deviation in the electrons trajectory, and the photocurrent density in the base is in the direction of the vector $\vec{i}$, so Eq. (6) can be rewritten as:

$$|\vec{J_b}(x)|\vec{i} = qD_n\frac{d\delta(x)}{dx}\vec{i} - q\mu_n\delta(x)|\vec{E}(x)|\vec{i} \tag{8}$$

By substituting $|\vec{E}(x)|$ from Eq. (7) in Eq. (8), the magnitude of the photocurrent density in the base in absence of the external magnetic field is found as:

$$|\vec{J_b}(x)| = q\left[\frac{\mu_p D_n - \mu_n D_p + 2\mu_n D_n}{\mu_p + \mu_n}\right]\frac{d\delta(x)}{dx} \tag{9}$$

Under the influence of the external magnetic field ($\vec{B_{ex}}$) shown in Fig. 1, the transportation phenomena equation (Eq. (6)) giving the photocurrent density in the base changes as below:

$$\vec{J_b}(x) = qD_n\vec{\nabla}\delta(x) + q\mu_n\delta(x)\vec{E}(x) - \mu_n\vec{J_b}(x) \times \vec{B_{ex}} \tag{10}$$

Noting Fig. 1, the above expression is rewritten as:

$$|\vec{J_b}(x)|\vec{i} = qD_n\frac{d\delta(x)}{dx}\vec{i} - q\mu_n\delta(x)|\vec{E}(x)|\vec{i} - \mu_n|\vec{J_b}(x)|\vec{i} \times |\vec{B_{ex}}|\vec{j} \tag{11}$$

By substituting $|\vec{E}(x)|$ from Eq. (7) in Eq. (11), the magnitude of the photocurrent density in the base in presence of the external magnetic field is obtained as: