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Development of an electronic load I-V curve tracer to investigate the impact of Harmattan aerosol loading on PV module pern2tkformance in southwest Nigeria

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the impact of the seasonal Harmattan aerosol loading on PV module efficiency at a station in Southwest Nigeria. To this end, a simple, open-source, cost effective electronic load I-V curve tracer was developed to compare the I-V characteristics of a pair of horizontally positioned 80 W monocrystalline modules for the duration of the Harmattan period. The control module was regularly cleaned manually and the other module left to accumulate the Harmattan dust deposits. In order to obtain the modules' characteristic parameters, an Arduino-based pulse width modulation *(pwm)* duty cycle was implemented to vary simultaneously, the gate-source voltages, V_{GS}, of two power metal-oxide semiconductor field-effect transistors (MOSFETs) acting as fast variable loads for the modules. Experimental results acquired from the prototype circuit demonstrate that this method provides a more accurate approach and faster response than the resistive load tracer method. The prototype instrument was able to measure and reproduce characteristic curves that are obtainable from the more expensive branded products. Resulting curves depict reduction in the short circuit current, I_{SC}, the current at maximum power, I_{MP}, the power output, P_{MP} and the efficiency, η of the dusty module by more than 18% in comparison with the control module over the measurement period.

1. Introduction

Inherent problems associated with PV systems include challenges peculiar to the climate and weather patterns of the locale in which the system is to be installed. Knowledge of weather conditions, particularly solar irradiance, one of the critical input factors required for evaluation of PV power generation, is pertinent for adequate system sizing.

Nigeria is a tropical country situated between 3–14°E of longitude and 4–14°N of latitude and supplied with ample amount of sunlight all year round; it's annual average daily solar radiation is about 5.25 kWh/m^2 per day, varying between 3.5 kWh/m^2 per day at the coastal areas and 7.0 kWh/m^2 per day at the Northern boundary, and an annual average daily sunshine of 6.25 h ranging between 3.5 h at the coastal areas and 9.0 h at the far northern boundary (Abdusalam et al., 2012). During the rainy season from May to October, the atmosphere is mostly cloudy and suffused with large amounts of water vapour, especially in the coastal, eastern and southern regions. The rains begin to recede in late October and soon after, say, middle November, the atmosphere becomes hazy, giving notice of the incoming dry Harmattan season. This is the seasonal southward migration of the dry weather emanating from the Sahara desert between November and March of the following year. It brings along with it the vertical aerosol loading of the atmosphere across the expanse of West Africa. The southward migration of this Harmattan dust front is associated with the migration of the Inter Tropical Discontinuity (ITD) weather system (Ojo, 1977). The ITD (also known as the Inter Tropical Convergence Zone, ITCZ) is the north-south movement of a zone of discontinuity or the boundary between the moist south-westerly, tropical maritime (mT) monsoon air mass originating from the Gulf of Guinea, and the hot, dry north-easterly tropical continental (cT) air mass blowing down from the Sahara Desert. By the end of January to mid February, the ITD holds a position of approximately 6°N and all regions north of this latitude will be under the influence of cT air mass, resulting in dry season conditions across West Africa (Ojo, 1977). Ede (7°44′20″N, 4°26′10″E), the southwest station in Nigeria under study, lies along the path of this front and very much receives both weather conditions. Therefore, between November and March, the Harmattan aerosol dust descends on the whole country. Invariably, solar irradiance reaching down is scattered and diffuse which in turn results in the degradation of PV system performance.

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1.1. Dust degradation

In designing and sizing backup systems, these weather patterns affecting insolation mentioned above are usually factored into the solar resource assessment otherwise the PV system energy requirement may not be accurately sized and the backup system could turn out to be inefficient. Dust deposition on PV modules is one of the issues hampering efficient performance of modules and has been studied by several authors (Ndiaye et al., 2013; Sulaiman et al., 2011; Kaldellis et al., 2011; Siddiqui and Bajpai, 2012; Mani and Pillai, 2010; Gupta, 2017; Sayyah et al., 2014; Tanesab et al., 2015; Saidan et al., 2016; Paudyal and Shakya, 2016). It was shown from these studies that dust deposition on PV modules caused a significant reduction in efficiency and energy yield of the modules. In urban areas, other aerosols, e.g., suspended particulate matter of different size distributions that can contribute to diminishing the efficiency of a module – soot, ocean spray, carbon monoxide exhaust from poorly maintained vehicles, chemical fallout from factories, all settle on PV modules. These particles possess light (photon) absorbing and scattering coefficients which ultimately contribute, to some degree, the attenuation of the incoming solar radiation and consequently the reduction in output energy of the module (Sayyah et al., 2014; Tanesab et al., 2015; Saidan et al., 2016; Paudyal and Shakya, 2016; Babatunde et al., 2009; Park et al., 2011; Wang et al., 2009).

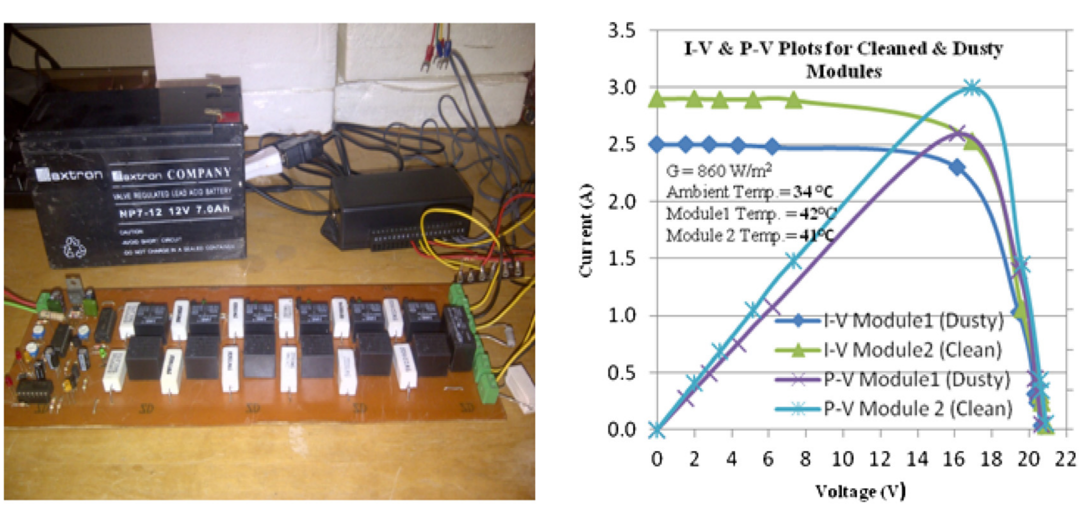
In Nigeria, visual inspection of solar street lights and mounted roof top PV modules in different cities across the country reveal that they are mostly caked with layers of accumulated dust and grime that have not been cleaned for a long time. Consequently, backup system batteries are usually not adequately charged by either *pwm* or MPPT charge controllers. A common method of assessing the electrical output performance of a PV module is by scanning the current - voltage (I-V) and power - voltage (P-V) characteristics of the module (Ndiaye et al., 2013; Kopp, 2012; Ramaprabha et al., 2015; Leite and Chenlo, 2010; Leite et al., 2012; Kuai and Yuvarajan, 2006). Performance indicators largely affected by dust deposition on modules are the short circuit current, I_{SC}, current at maximum power, I_{MP}, maximum power, P_{MP} and efficiency, η. This work investigates the impact of the 2016/2017 seasonal Harmattan aerosol loading on PV modules in Ede by developing an I-V curve tracer with a power MOSFET acting as the load. Characteristic curves of two modules, one the clean (control) module and the other with dust accumulation on it are then compared in order to observe the effect of dust on PV performance. The work is also an improvement on the resistive load I-V curve tracer presented in a previous work (Willoughby et al., 2014).

1.2. I-V curve tracers

Apart from measuring I-V characteristics, curve tracers are also fast functional instruments for checking observable signs of module performance, defects, weathering and degradation. In recent past, several studies have investigated the effect of dust, soiling, shading and weather on PV efficiency and degradation using different kinds of devices (Ndiaye et al., 2013; Hamdaoui et al., 2009; Kopp, 2012). Obtaining accurate results is best achieved by scanning the module characteristics using I-V curve tracers. PV I-V characteristics are typically obtained by varying a load across the module. Different designs of I-V curve tracers abound in literature and are commercially available. A detailed comparison of six different procedures of the designs of I-V curve tracers that have been reported in literature is reviewed by Durán et al. (2008). A number of commercially available I-V curve tracers are available to PV manufacturers, system integrators, contractors and installers with prices dependent on the levels of sophistication, durability, and performance (Renewable Energy Innovation). Ndiaye et al. (2013), investigated the effect of dust on PV module I-V/P-V characteristics in the Sahelian desert environment after a year of exposure of mono- and poly crystalline modules without cleaning. The "I-V 400" instrument used is a hand held PV tester suitable for ordinary and scheduled maintenance of PV systems. It also features temperature and radiation measurement capabilities. From their measurements, they deduced a maximum power output loss from 18% to 78% and 23% to 80% for the poly- and mono crystalline modules respectively.

Due to the prohibitive cost of a branded tracer, a simple, minimalist, cost effective instrument with available off-the-shelf components was designed for the present purpose and for future related experiments by taking advantage of the Arduino open source platform with a view to future design upgrades with more features.

One of the designs enumerated in Renewable Energy Innovation, describes a variable resistive load which seems to be the cheapest and easiest tracer method to implement. In Willoughby et al. (2014), a resistive load type was implemented that comprised of rapidly varying resistive loads centred on power resistors connected to relays and controlled by an electronic circuitry. A 555 astable oscillator transmitted clock pulses to the clock terminal of a 4017 decade counter which in turn produced a sequence of pulses that successively turned on relays via driver transistors. The I-V characteristic points of the module were measured accordingly by the consecutive selection of the relays which were each connected to a selected load resistor to determine the operating point on the I-V curve as seen in Fig. 1(a) and (b). A Pace XR5 eight channel data logger was connected to record the currents and voltages as well as the irradiance. This method of selection of load resistors via relays has its shortcomings, not



(a) **(b)**

Fig. 1. (a) Photo of resistive load tracer from previous work, (b) I-V & P-V plots obtained.