Effect of Different Factors on the Leakage Current Behavior of Silicon Photovoltaic Modules at High Voltage Stress

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***Abstract*—Leakage current is one of the determinants of potential-induced degradation (PID) of the photovoltaic (PV) module. Effects of different parameters such as module surface temperature, surface wetting, salt and dust accumulation, and aging condition on high-voltage-stress (HVS) leakage current of the crystalline PV module are investigated in the laboratory. In this research, a novel notion on HVS-leakage-current-modulating parameters has been introduced, which is useful to assess the HVS degradation at different climates. The leakage current increases moderately with the increase of module surface temperature, and it increases drastically during the surface wetting condition. The leakage current under 1000-V stress is 5.04, 5.82, and 35.55 μA/m^2 at 25 °C (50% relative humidity), 60 °C (8% relative humidity), and 45 °C (wet) conditions, respectively. The presence of salt also increases the leakage current almost linearly. A slight amount of dust (2 g/m^2) on the module surface was found to trigger the wet leakage current to a considerable limit. Tiny dust particles have a capability to attach with some ionic compounds, where Na ions are dominant from the coastal area that prompts the leakage current of the PV module. Long-term field operation known as aging of the PV module *reduces* the electrical resistance of ethylene vinyl acetate; consequently, the leakage current, as well as PID, increases significantly.**

***Index Terms*—High voltage stress (HVS), leakage current, photovoltaic (PV) module, salt dust and aging effect, temperature.**

I. Introduction

HIGH voltage stress (HVS) on modules in large photovoltaic (PV) power plants is swelling day by day with increasing string size. As a consequence of HVS, the leakage current flows from the module frame to solar cells or vice versa, depending on the voltage stress polarity [1]–[3]. During the leakage current flow, ions migrate from the glass surface toward the solar cell and accumulate into an antireflection and passivation layer. Under sufficient negative voltage stress, Na^+ ions make way within the emitter region via stacking faults and, then, cross the n^+-p junction. Once the positive ions enter the stacking fault, they are neutralized by accepting free electrons of the emitter and produce one-dimensional metallic line; as a consequence, ohmic shunt is produced, and ultimately degradation of the PV module occurs [4]. The surface polarization effect can also hamper the PV module performance, where positive or negative charges accumulate in the ARC/SiO_2 layer as a result of negative or positive bias; this increases the surface recombination of electrons and holes. Degradation of the PV module caused by such causes as mentioned above is known as potential-induced degradation (PID). The leakage current characteristic of a PV module is one of the determinants for PID. Recently, Kang *et al.* [5] reported that the power loss due to PID of a PV module at a certain stress condition is proportional to the leakage current flow at that stress condition.

Generally, PV module's leakage depends on different factors such as: 1) module factors (glass surface resistance, glass composition, and encapsulant resistance); and 2) system or environmental factors (string voltage, module surface temperature, humidity, rain, dew or mist, dust, etc.) The dependence of the leakage current on the module temperature and humidity at a voltage stress of 600 V has been reported [6]. Dhere *et al.* [7] also reported the effect of temperature and humidity on the PV module leakage current at a fixed voltage stress of 600 V.

On the other hand, dust and salt (at coastal area) accumulation on the PV module surface are the common phenomena. Rahman *et al.* [8] report that the PV module efficiency decreases by 1.34% due to 0.01-g/cm^2 dust deposition on the module surface. Both dust and salt mixed with a water film generated from the dew or fog or mist alter the glass surface properties [9], [10]. Suzuki *et al.* [11] found that PID of the PV module was increased due to extent of salt-mist preconditioning.

Moreover, the PV module performance is hampered due to long-term field aging. There is a possibility of moisture ingress, chemical leach out of the encapsulant materials due to field aging. Recently, Sinha *et al.* [12] have reported that discoloration of encapsulant decreases the electrical insulation of the PV module. Therefore, there is a significant effect of aging on the HVS resistance of the PV module.

Manuscript received July 10, 2017; revised September 4, 2017, March 20, 2018, and May 4, 2018; accepted May 18, 2018. This work was supported by the University of Malaya, Kuala Lumpur, Malaysia, under Project RP016A-15SUS and Project UM.0000067/HME.OM, UMPEDAC-2016. *(Corresponding author: M. Hasanuzzaman.)*

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Digital Object Identifier 10.1109/JPHOTOV.2018.2841500

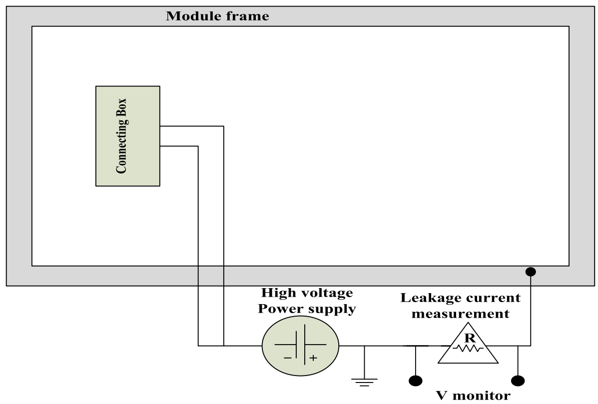

Fig. 1. Leakage current measurement circuit [13].

The above literature shows that although the effect of temperature and humidity on the PV module leakage current has been studied at a fixed voltage stress, it seems important to evaluate these effects under varying voltage stresses with a greater potential range. In addition, the effect of salt on the leakage current has rarely been conducted. On the other hand, the effect of dust particles and field aging on the HVS leakage current of PV modules, especially respective to Malaysia's weather condition, is rare in the literature. In order to assess the HVS degradation of the PV module under different tropical environmental conditions, it is necessary to understand fully about the impact of different operating parameters on the PV module's HVS leakage current. Moreover, a comparative severity feature of different parameters is useful to find out the appropriate prevention technique of the HVS degradation. Therefore, in this research, the effect of various factors such as module surface temperature, surface wetting, salt deposition, dust deposition, and long-term field aging on the leakage current characteristic is examined at different voltage stresses, and for the first time, a comparative impact of different factors on the leakage current characteristic is presented.

II. Research Methodology

A. Experimental Setup

The experimental work has been carried out in Solar Testing Laboratory, Wisma R&D, University of Malaya, to investigate the leakage current behavior of the PV module under the HVS at different conditions. Fig. 1 shows the leakage current measurement setup. A high-voltage dc power supply has been used to apply the HVSs to the PV module. The module frame was connected to the negative and module connectors to the positive terminals of the dc power supply. A 10-kΩ resistor was connected in series between the frame and the dc power supply to measure the leakage current flow. The voltage produced across the resistor was recorded, from which the leakage current is calculated. The module surface temperature was increased by placing the PV module at a homemade solar emulator made of halogen bulb light. The solar emulator is composed of 90 OSRAM halogen bulbs, where each bulb capacity is 90 W. Module bottom surface and top surface temperatures were monitored by using a k-type thermocouple. The module temperature has been calculated from the average of the bottom and top surface temperatures.

TABLE I
Specification of PV Modules Taken as a Sample in the Experiment

Parameters	Module A	Module B	Module C	Module D
Manufacturer	Shaiyang	Endaupv	Mitsubishi	Shell solar
Material	Mono crystalline	Poly crystalline	Poly crystalline	Mono crystalline
No. of Cells	4×9	6×10	4×9	4×9
Size (mm)	1200×545	1666×997	1495×67	1200×527
Max. Power	90W	250W	125W	85 W
Voc (V)	22.03	36.96	21.8	22.2
Isc (A)	5.30	8.8	7.9	5.45
Cell Size (mm)	125×125	156×156	156×156	125×125

B. Photovoltaic Module Samples

Different types of PV modules have been used in this experiment. The detail module specifications under standard test conditions are shown in Table I. Module type "A" was used to investigate the effect of module surface temperature, surface wetting, salt, and different amount of deposited dust on the HVS leakage current behavior. Another three types of PV modules (such as B, C, and D) are selected for the investigation of the onsite dust deposition effect on the HVS leakage current. The impact of aging on the HVS leakage current performance has been examined by considering PV modules of two different manufacturers as B and C. The leakage currents of new modules of the respective type were compared with the leakage current values of similar modules aged at different time periods.

C. Instrumentations

Different types of instruments such as high-voltage dc power supply, multimeter, thermocouple, digital data taker and conductivity meter, electric balance, etc., were used in this study. For the leakage current measurement, a programmable high-voltage dc power supply (Brand name: Hi-Pot Tester; Model: DU-332, Delta United Instruments, Taiwan) has been used. The power supply is capable to produce the voltage ranging from 0 to 6 kV for dc and from 0 to 5 kV for ac. The voltage developed across the resistor has been measured by using a digital multimeter. A digital data logger (Brand: Data Taker model: DT-80) is used to monitor the temperature of the PV module surface by using a k-type thermocouple. The amount of dust and salt is weighted by using an electronic balance. The conductivity and salinity of the aqueous solution of salt were measured by using a smart conductivity bench meter (brand name: STARTER 3100C). The dust particles are characterized to examine the microstructure by using a field emission scanning electron microscope (FESEM) (Brand: Hitachi Model: SU8220).

D. Test Conditions

To measure leakage current under different conditions, high dc voltage stresses from 100 to 1500 VDC was applied on the module at a step of 100 V, wherein the following test conditions were maintained.

1) Module Temperature Impact Testing: The module temperature has been calculated from the average of the bottom and top surface temperatures detected by data logger and thermocouples. The module temperature has been increased as 25, 30, 35, 40, 45, 50, 55, and 60 °C by placing the PV module under the solar simulator, and the respective leakage current has been measured. The maximum module temperature at Kuala Lumpur, Malaysia, was found near about 60 °C [14], and for this reason, in this work, the leakage current was measured up to 60 °C. Surface relative humidity (RH) was calculated from the ambient RH, the ambient temperature, and the respective module temperature. The ambient RH was monitored by a humidity meter.

2) Module Surface Wetting Impact Testing: The standard test procedure according to IEC 61215:2005, 10.15 has been followed to perform the wet leakage current test. The PV module surface was wetted by spraying distilled water near about 200 ml/m^2. The wetted module's temperature was increased as 25, 30, 35, 40, and 45 °C by placing the module under the solar simulator, and the respective wet leakage current has been measured.

3) Salt Deposition Impact Testing: Purified sea salt was used to investigate the salt effect on the PV module's leakage current characteristic. Aqueous solutions having different weights of salt such 1, 2, 3, 4, and 5 g in a 300-ml solution were made. 200 ml/m^2 of each solution was sprayed on the module surface, and the respective leakage current was examined at a temperature of 25 °C. Salinity and conductivity of the aqueous solution were measured by the conductivity meter STARTER 3100C.

4) Dust Deposition Impact Testing: The role of on-site dust deposition on the PV module leakage current has been investigated by placing different modules at outdoor for a long time of more than one year, and their respective wet leakage current behavior has been measured. To investigate the effect of dust particle deposition on the leakage current at a room temperature of 25 °C, several weights of dust such as 2, 3, 5, 10, and 15 g/m^2 were homogeneously spread over the module surface, and 200-ml/m^2 distilled water was also sprayed uniformly on the module surface. Before every experiment, the module surface was washed properly with distilled water and dried at 45 °C for 30 min.

5) Aging (Long-Time Field Expose) Impact Testing: The effect of aging (long-time field expose) of PV modules on their leakage current characteristics has been examined by using two different types of modules field aged at the different time periods. The wet leakage current densities of the modules were measured at 25 °C. To investigate the change of temperature-dependent activation energy due to aging, the wet leakage currents of new and aged modules at different module temperatures have been measured.

III. Results and Discussion

A. Effect of the Module Temperature

The PV module's leakage currents at different HVSs and different module temperatures are shown in Fig. 2. The surface RH changes with the surface temperature, and obtained surface RHs are 50%, 37%, 28%, 21.5%, 16.5%, 12.8%, 10%, and 8% at module temperatures of 25, 30, 35, 40, 45, 50, 55, and 60 °C, respectively. The leakage current increases exponentially with the increase of voltage stress. Very slight amount of leakage current is increased due to an increase of module temperature, as presented in the inset of Fig. 2. This may be due to a decrease of resistivity of glass and ethylene vinyl acetate or other encapsulant material at a higher temperature, for example, soda-lime glass resistivity decreases by 0.002 Ω/°C [15]. The leakage current increasing rate also increases with the voltage stress. The obtained increasing rates at voltage stresses of 600, 1000, and 1500 V are 0.0067, 0.0222, and 0.0524 μA/m^2/°C, respectively.

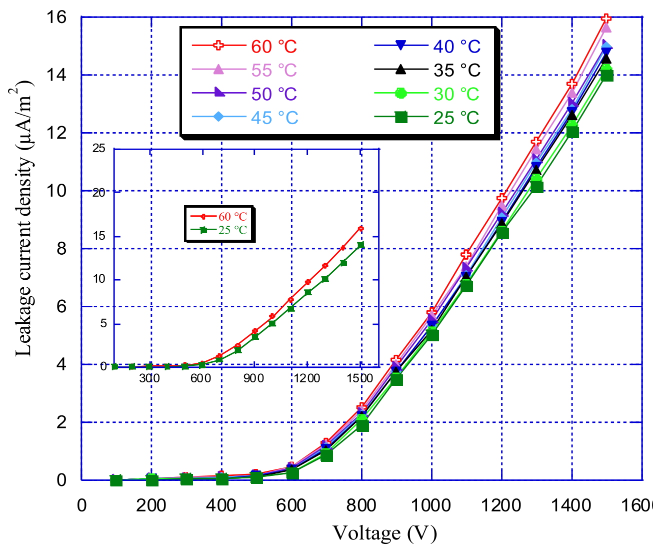

Fig. 2. Leakage current behavior as a function of HVSs at different module temperatures (surface RH at 25 and 60 °C are 50% and 8%, respectively).

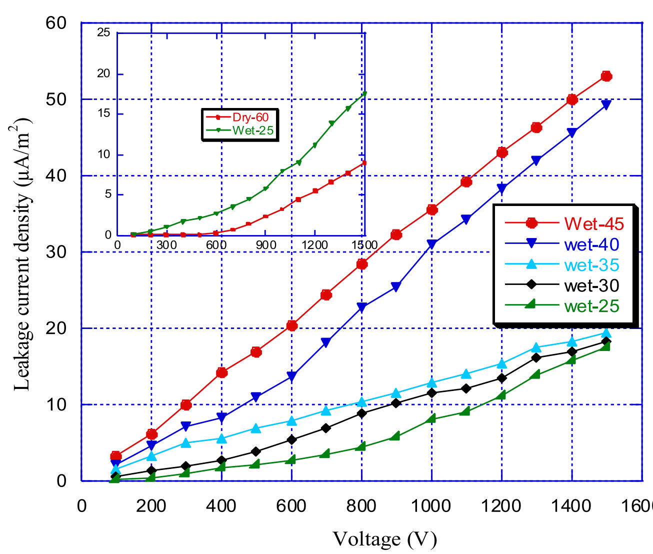

Fig. 3. Variation of wet leakage current as a function of HVS at different module temperatures.

B. Effect of the Wet Surface Condition

The PV module surface can be wetted due to high RH, dew or mist of the morning, rain, etc. Fig. 3 shows the HVS leakage current of the surface-wetted PV module at different temperatures.

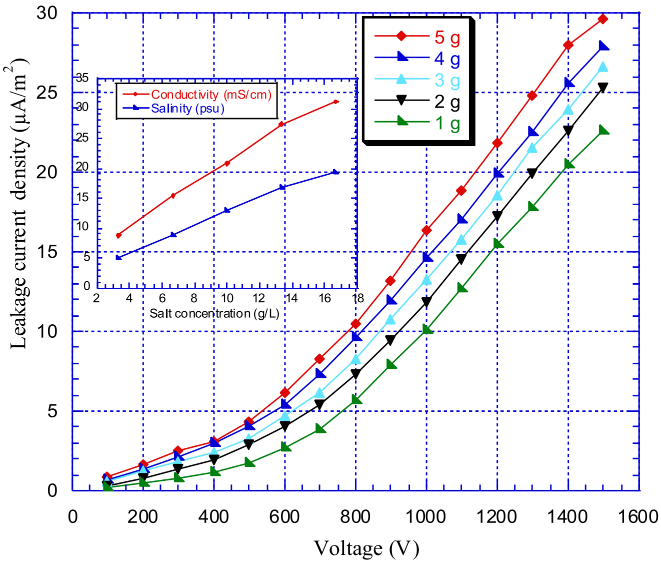

Fig. 4. Voltage-stress-dependent leakage current behavior at different salt concentrations of the module surface water film.

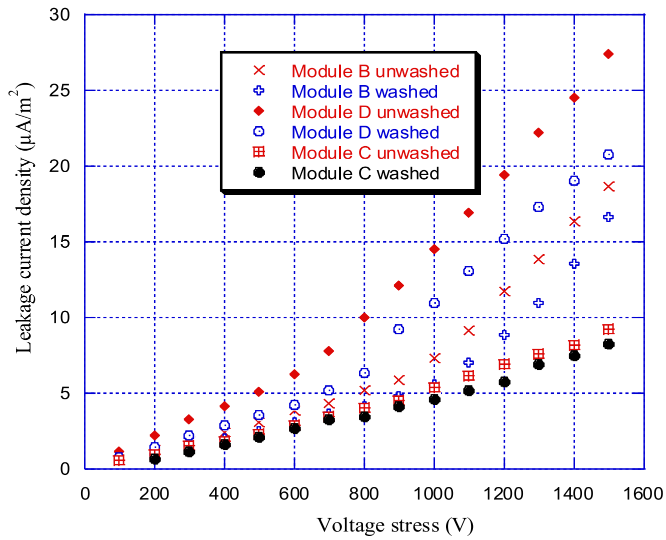

Fig. 5. On-site dust effect on the HVS leakage current of different PV modules: Modules B, C, and D.

TABLE II
EFFECT OF ON-SITE DUST DEPOSITION ON THE HVS (1000 V, 100% RH, AND 25 °C)

Module type	Material	Leakage current with dust (μA/m^2)	Leakage current without dust (μA/m^2)	Escalation (%)
B	Poly crystalline PV module	7.26	5.53	31.25
C	Poly crystalline PV module	5.41	4.61	17.50
D	Mono crystalline PV module	14.54	10.98	32.35

The wet leakage current drastically increases with the increase of the module temperature The leakage current versus voltage stress curve becomes linear after a module surface temperature above 35 °C. The amount of leakage current with the wet surface at room temperature has been greater than that found with the dry surface at 60 °C, as shown in the inset of Fig. 3. In the presence of a water film, the metal content of the soda-lime glass is ionized to produce charge carrier, and as a consequence, the leakage current increases [16]. As the temperature increases, the generation of charge carrier increases, thereby giving rise to the leakage current. At the high temperature and wet surface condition, the HVS leakage current of the PV module increases drastically, which results in an increase of the PID rate.

C. *Effect of Salt Mix Water on the Module Surface*

Salt can be deposited on the PV module placed near the coastal area. Fig. 4 shows the voltage-stress-dependent leakage current behavior at different salt concentrations of module surface water. A significant rise of leakage current has observed with the increase of salt concentration. As the extent of salt in the water film increases the conductivity and salinity of water film, both are linearly increased, as shown in the inset of Fig. 4, and subsequently, the PV module glass surface resistivity is decreased. Ions from the salt can be used as the charge carrier, which enhances the leakage current. The increasing rate of leakage current is also raised with the escalating of voltage stress. The obtained rates are 0.84, 1.53, and 1.65 μA/m^2/g at 600, 1000, and 1500 voltage stress, respectively.

D. *Effect of Dust*

Dust accumulation on the PV module is a very common physical process. Different amounts of dust can be accumulated at different places. To examine the effect of on-site deposited dust on the leakage current of the PV module, three distinctive PV modules (made by various producers, for example, B, C, and D) from the PV plant set in the UMPEDAC solar garden have been taken.

The wet leakage current has been measured prior and then afterward washing conditions. The module surface was washed with refined water, and in the wake of drying, isopropyl alcohol was utilized for the further cleaning process. Fig. 5 shows the leakage current of three distinct modules at various voltage stresses. All modules show high leakage current at the unwashed condition contrasted with the washed condition. Table II shows the on-site dust effect on the leakage current values of different PV modules at a voltage stress of 1000 V. Leakage current values are increased by 31.25%, 17.50%, and 32.35% due to dust deposition for modules B, C, and D, respectively. Fig. 6 shows the FESEM of dust particles. Dust particles are heterogeneous in size and distributed from as larger as several micrometers to as small as 18 nm in diameter. Small particles are attached to the larger particles. Small particles are brighter than larger particles, which indicate electron charging during imaging. Small particles possess charging state that allows them to attach with the larger particles [10].

At the coastal area, these tiny dust particles can easily attach with ionic compounds (salt) due to their charging nature. As a consequence, the salt is easily deposited on the PV module

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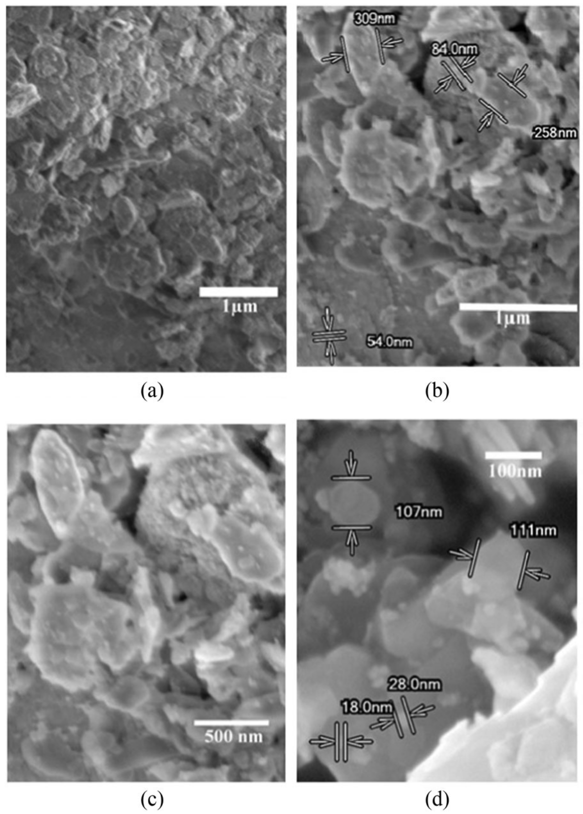

Fig. 6. FESEM images of dust particles at different resolutions. (a) 10 k. (b) 20 k. (c) 30 k. (d) 70 k.

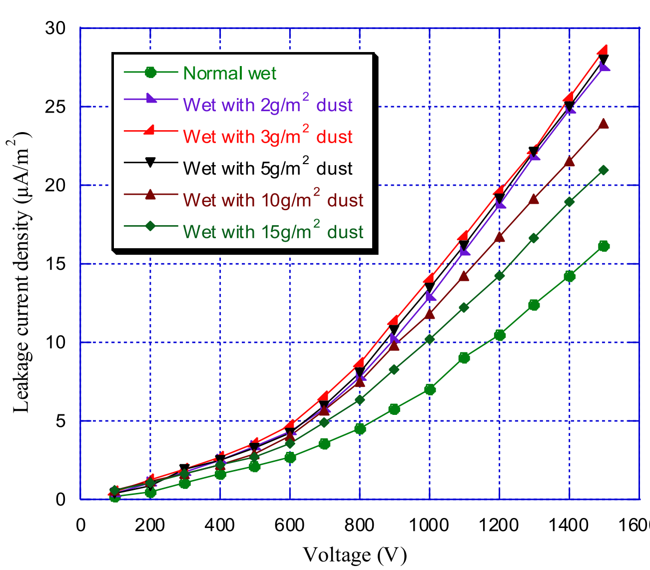

Fig. 7. Voltage-stress-dependent leakage current at different amount of dust accumulation on the PV module surface.

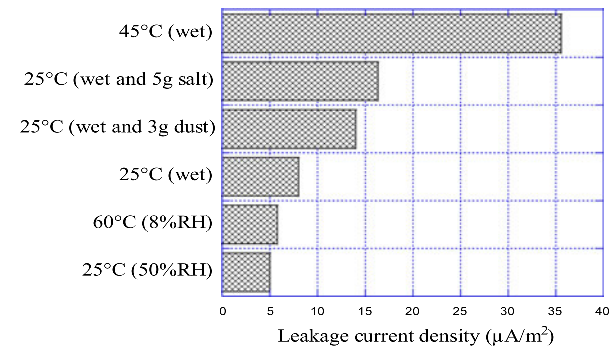

Fig. 8. Relative changes in the leakage current at 1000-V stress at different parameters' impact on the HVS leakage current of the PV module.

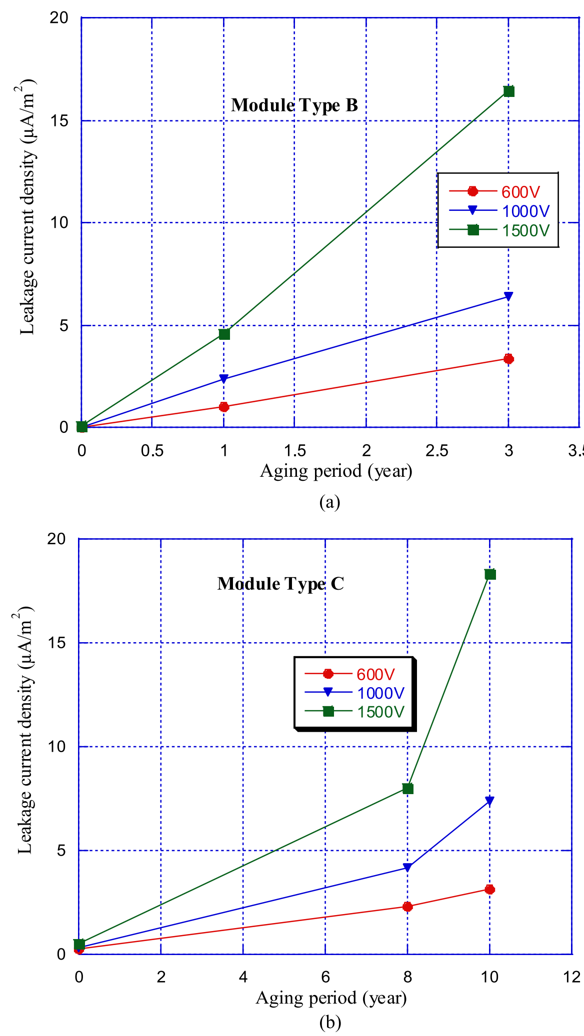

Fig. 9. Effect of the aging period on the wet leakage current density. (a) Type "B" module. (b) Type "C" module.

surface [17]. The variation of the wet leakage current due to the accumulation of different amount of dust mixed water (i.e., mud) on "A"-type module is shown in Fig. 7. All curves follow an exponential trend line, and the leakage current increases exponentially with the increase of voltage stress. Initially, a sharp increase of leakage current has been observed due to an increase of dust amount; then, after reaching the highest value, the leakage current decreases gradually. Because, dust contains alkali and alkaline earth metal, ions dissolve in the water during the mud formation and produce an active solution. As a consequence, the glass surface conductivity increases [12]. However, after 3 g/m^2, the metal ion dissociation is reduced due

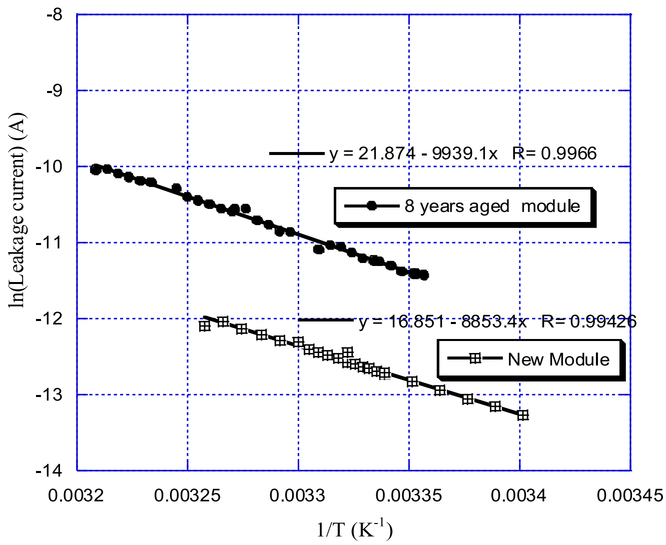

Fig. 10. Inverse-temperature-dependent wet leakage current behavior of new and eight-year aged PV module type C.

to the decrease of dilution of the mud so that the highest value of the leakage current has been found at 3-g/m^2 dust. Maximum values of the leakage current are 4.74, 14.00, and 28.55 μA/m^2 at voltage stresses of 600, 1000, and 1500 V, respectively.

A comparative feature of the impact of different parameters such as module temperature, surface wetting, dust, and salt deposition has been presented in Fig. 8. The wet surface condition is more severe than the dry surface condition, although the module temperature is as high as 60 °C. Under wet surface conditions, the module temperature shows higher impact on the HVS leakage current, followed by salt and then dust deposition.

E. Effect of Aging

Fig. 9 shows the wet leakage current density of two PV module types "B" and "C" aged at different time periods. The leakage current increases exponentially with aging. As a consequence of long-time field aging, the chemical changes of encapsulant material bring about the decline in its insulating property, which, in turn, escalates leakage current generation [12], [18]. The temperature-dependent wet leakage current behavior of new and near about eight years field aged module in Fig. 10. The leakage current has been measured under 1500-V stress.

The activation energy of the leakage current has been calculated by using the Arrhenius equation as follows [19]:

$$I_{\mathrm{LC}} = I_{\mathrm{LC0}} \exp^{-[E_a/k_b T]}$$

$$\ln I_{\mathrm{LC}} = \ln I_{\mathrm{LC0}} - (E_a/k_b) \times \frac{1}{T}$$

where I_{LC} is the leakage current, I_{LC0} is the leakage current at temperature 0 K, E_a is the activation energy, k_b is Boltzman's constant ($k_b = 8.617 \times 10 - 5$ eV/K), and T is the module's absolute temperature. From the slopes of the curves, the respective activation energy has been calculated. The activation energy is increased from 0.763 to 0.856 eV due to eight-year aging. This climb of activation energy is comparable with the reported activation energy increase at higher humidity as: at high RH (95% RH), activation energy values were around 1.0–0.8 eV, and at low RH (10% RH), activation energy values were around 0.8–0.6 eV [1].

IV. Conclusion and Recommendation

A significant effect of the module temperature, surface wetting, salt, and dust particle accumulation on the PV module's leakage current has been obtained. The major inferences that are obtained from the present research work are enumerated as follows.

1) Leakage current increasing rates at voltage stresses of 600, 1000, and 1500 V are 0.0067, 0.0222, and 0.0524 μA/m^2/°C, respectively.
2) A drastic enhancement of the leakage current is observed due to an increase of the module surface temperature at the wet condition, and the leakage current values at voltage stresses of 600, 1000, and 1500 V are 20.36, 35.55, and 53.06 μA/m^2, respectively, at 45 °C and under the wet condition.
3) Increasing rates of the leakage current in the presence of salt at voltage stresses of 600, 1000, and 1500 V are 0.84, 1.53, and 1.65 μA/m^2/g, respectively.
4) A charge containing state of the smaller dust particles is observed, which can be easily attached to the ionic compound (like salt) especially in coastal regions. The maximum leakage current is obtained for 3-g/m^2 dust deposition, and the leakage current value is 14 μA/m^2 at a voltage stress of 1000 V under the surface wet condition.
5) The PV module resistance to flow the leakage current at HVS is deteriorated substantially as a consequence of long-time field aging.

The leakage current is promoted due to the wet surface condition of the PV module, which is further enhanced by dust accumulation. A hydrophobic and self-cleaning glass is recommended to be used for the control and prevention of leakage current generation, thereby reducing PID of the PV module.

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