

Diagnostics of PV Modules Using Time Domain Reflectometry

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Abstract—In photovoltaic (PV) module diagnostics, the methods most frequently used are based on measuring DC characteristics (mainly *I-V* curves). In real installations, PV modules are combined with inverters that operate on a high frequency and are connected to a grid. With this in mind, it can also be very useful to know certain AC parameters of the PV modules such as impedance. The method of examining the distribution of the impedance of the module (such as in the case of transmission lines) is called Time Domain Reflectometry (TDR). By a specific distribution of the impedance, it is possible to find the location and to determine the nature of a defect. Moreover, this method can also be used to differentiate modules that have the same nameplate values.

Keywords—PV module, Time Domain Reflectometry (TDR), CIGS degradation, PV modules diagnostics.

I. MODELLING OF PV MODULES

A. DC model

PV modules are mostly modelled by the one-diode or two-diode static model [1] (but in the case of illuminated modules the second part can be disregarded) as described by the equivalent circuit in Fig. 1. This circuit is given by the following equation [1]:

$$I_{PV} = I_{PH} - I_0 \left[\exp \left(\frac{q(V_{PV} + I_{PV}R_S)}{nkT} \right) - 1 \right] - \frac{V_{PV} + I_{PV}R_S}{R_{SH}} \quad (1)$$

where I_{PV} is the module current, I_{PH} is the photocurrent generated by light, I_0 is the reverse current, q is the electron charge, V_{PV} means the module voltage, R_S stands for the series resistance, η is the diode factor, k denotes the Boltzmann constant, T is the temperature and R_{SH} denotes the shunt resistance.

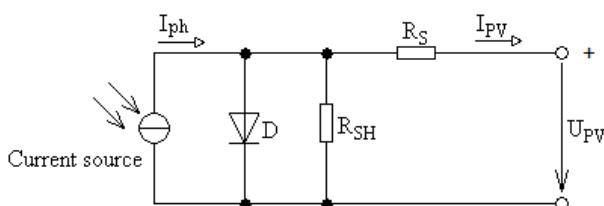


Fig. 1. DC equivalent circuit of a PV solar cell or module

The parameters of an equivalent circuit are mostly determined by measuring the *I-V* curves of the module (flash tester, solar analyzer).

B. AC model

An AC model of a PV cell includes elements from a DC model and also includes certain dynamic ones such as diode resistance (R_D), transition (C_T) and diffusion capacitance (C_D). The same model, as well as the correspondent equivalent circuit (Fig. 2), can also be used for an AC model of a PV module [2]. Equation (1) then can be rewritten as follows [3]:

$$I_{PV} = I_{PH} - I_0 \left[\exp \left(\frac{q(V_{PV} + I_{PV}R_S)}{nkT} \right) - 1 \right] - \frac{V_{PV} + I_{PV}R_S}{R_{SH}} - C_T \frac{d(V_{PV} + I_{PV}R_S)}{dt} - C_D \frac{d(I_{PV} + I_{PH})}{dt} \quad (2)$$

Dynamic parameters can be determined under dark conditions or under irradiation, but unlike static parameters, dynamic parameters are strongly influenced by irradiation. AC measurement methods that allow the parameter calculation include impedance spectroscopy [4], *C-V* measurement [2] and the impedance analysis method [5]. Knowledge of the AC parameters enables calculation of other parameters as well, e.g. doping concentration (N), breakdown voltage (V_B) and donors density (N_D).

II. TIME DOMAIN REFLECTOMETRY METHOD

In a real PV module, the single cells are connected in

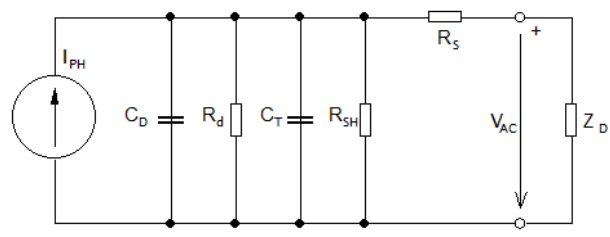


Fig. 2. AC equivalent circuit of PV solar cell or module

series, what means that each of the parameters identified by the previously mentioned methods represents only a sum of the contributions from the individual cells. This problem can be solved by time domain reflectometry.

TDR is a method mostly used to localize defects in transmission lines [6]. Not only the location of the defect but also the nature thereof can be determined using TDR. The method is based on sending a simple signal (such as a 1 Volt Step Wave) to a PV module and measuring the waveform of the reflected voltage wave that is sent back to an oscilloscope. Defective PV cells also have different values of impedance due to different values of capacitance and resistance. Defective PV cells that act like a short circuit or an open circuit within the module result in specific differences from the PV module in the measured reflected wave. By comparing the differences in the patterns of the waves reflected by both good, i.e. properly functioning, and defective PV modules, the defective PV cells inside the module can be located and the specific cause of failure can be determined.

A big advantage of this method is that no special equipment is required. To determine the static parameters, flash testers or solar analyzers are required, which are specialized instruments that are suitable only for characterizing photovoltaic devices. In contrast, the TDR method only requires a pulse generator and an oscilloscope, which can be used in other areas of electronics and are thus more readily available. Thanks to its ability to locate a defect in a line, TDR can also be used to find faulty PV modules directly in the strings without the need to disconnect the modules.

III. EXPERIMENTS

A. Procedure and evaluation

The TDR method was applied on a series of CIGS PV modules of various generations but of the same nominal power. To ensure repeatability of measurement, the modules were measured under dark conditions.

The method is as follows: a 122.5 mV Step Wave (frequency 1 kHz and rise time 80 ns) from a pulse generator is applied to the terminals of the PV panel. The wave crosses all the individual PV cells in the panel and is reflected by them. A filter for noise limitation is then used and finally the signal reaches the output terminals, where it can be measured by the oscilloscope (Fig. 3). By comparing the reflected waves to panels of the same type, it is possible to determine whether the PV panel being measured is working properly or whether some of its cells

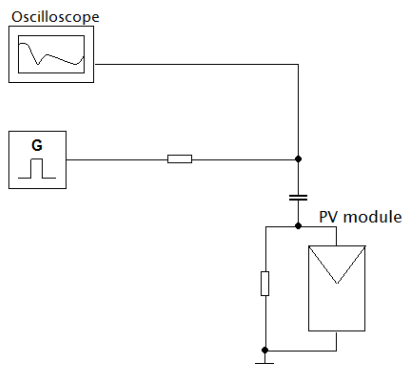


Fig. 3. The block diagram for measurements using TDR

have defects. Evaluating the TDR is then fairly easy [7]:

- Taking into account the time of the wave reception by the oscilloscope in the case of a good module, a difference signals indicate that there is a defective cell within the panel/array.
- A larger amplitude of the peaks of the voltage wave according to the peaks obtained on a good PV module of the same type indicates that the defective PV cell is acting like a short circuit inside the panel/array.
- A larger amplitude of the valleys of the voltage wave according to the valleys obtained on a good PV module of the same type indicates that the defective PV cell is acting like an open circuit inside the panel/array.
- The rising of the response voltage wave to a certain level relates to an increase in the string impedance, which may indicate a degradation of the connectors.

B. Results obtained

To verify the defects found by TDR, flash tests of the same modules (same generation) were performed. A comparison of the values obtained by the flash tests by Standard Testing Conditions (STC) is shown in the following table (Tab. 1).

TABLE I.
FLASH TEST VALUES BY STC

Number	33	34	35	36
I_{SC} (A)	1,698	1,717	1,667	1,709
V_{OC} (V)	92,23	90,201	91,277	87,139
η (%)	11,53	10,96	10,86	10,35
FF (%)	69,18	66,46	67,05	65,27
MPP (%)	108,313	102,948	102,047	97,196
V_{MPP} (V)	71,217	69,167	69,459	64,599
I_{MPP} (A)	1,521	1,488	1,469	1,505
R_S (Ω)	7,8	7,9	8,5	8,9
R_{SH} (Ω)	2082,3	2270,2	1815,4	1683,7

A corresponding graph of the TDR method is shown in Fig. 4.

Because of the different technology of producing single generations of the same type of the PV modules, their

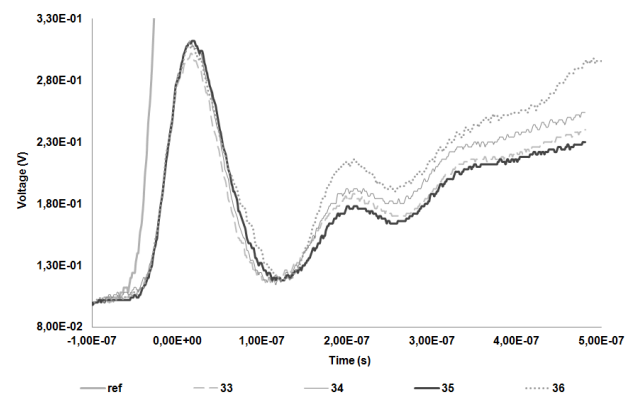


Fig. 4. Measured waves on CIGS modules by TDR

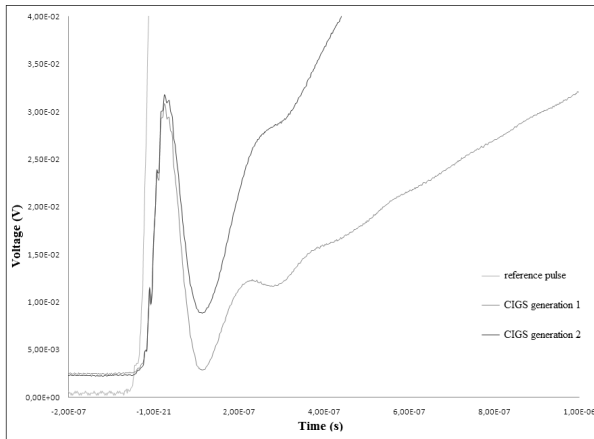


Fig. 5. Comparison of TDR graphs of two generations of CIGS PV modules

impedance profile should also be different. Two different generations of the same type of PV module were measured and the results confirmed that they can be differentiated using the TDR method (Fig. 5).

IV. CONCLUSION

DC and AC models of the PV modules were presented and an analysis of the TDR measurement method was performed. To verify the TDR method, flash tests of the measured modules were also made. Tab. 1 and Fig. 4 show the correlation between both methods. PV module number 36 presents a significantly different waveform from all the others, especially on its second peak. This indicates that some kind of failure or degradation exists on the PV panel. Flash test values clearly indicate certain defects on the same PV module.

Although the TDR method is used only to find defects, experiments made on two different generations of the same PV module proved that it can be utilized on a much wider scale. Two different generations of the same PV module type and the same producer showed a different response to the same impulse (Fig. 5). These differences can cause major problems in real PV systems, because the combination of more PV module generation can, by using improper inverters, have different degradation rates.

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