CELL TECHNOLOGY INDEPENDENT I-V-CURVE MEASUREMENT OF PV MODULES UNDER REAL OPERATING CONDITIONS

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ABSTRACT: As commonly known the most significant method to describe the performance characteristic of PV modules is the measurement of I-V curves under real operating conditions. Although there is no need to reinvent the wheel since all recognized PV test-facilities and a number of manufacturers of PV modules are using their specific equipment. The purpose of the here described method lies furthermore in the set up of an outdoor test facility, which can measure a broad spectrum of different technologies of PV modules together without time-consuming adaptation of the measurement equipment.
Keywords: PV Module, Qualification and Testing, Experimental Methods

1 DESCRIPTION OF THE EQUIPMENT

1.1 Hardware

1.1.1 Control PC

The heart of the testing equipment consist of a 4-channel simultaneous 800 kHz sampling 16-bit A/D PXI-board from National Instruments type PXI-6120. The control of the analogue output channels of this board can be synchronised to the analogue input reading.

Figure 1: Controller PC: 4-channel simultaneous sampling DAQ card, 96-channel digital I/O card (National Instruments PXI-8186, PXI-6120 and PXI-6509)

The signal conditioning is done with high accuracy active signal transducers with a bandwidth of 300 kHz (voltage transducer, LEM CV 3-200) and 500 kHz (current transducer LEM CT 10). The maximum dynamic of the load sweep is limited actually to 2 kHz. Faster sweeps can cause transient behaviour in the measurement system as it can be seen in figure 6 and figure 8.

1.1.2 Variable electronic load

The analogue output of the PXI-6509 is connected to the voltage programming input of three bipolar operational power supplies KEPCO BOP 100-4M.

The BOP is used as a high-speed sink, which transmits arbitrary load profiles directly to the PV modules under test.

Depending on the length of the power conducting cables the current cause significant voltage drops in the power line between PV module and BOP. However, it is **not** desirable to connect the PV module and BOP in 4-wire mode (2 power + 2 sense lines), because the BOP voltage sense regulation compensate only drops up to 0.5 volt per wire. Furthermore the regulation circuit of the BOP can create additional dynamic effects in case the overall capacity is above 0.2µF and the inductance is above 0.5mH.

Figure 2: 4-quadrant bipolar operating power supplies KEPCO BOP 100-4, sink mode, program controlled arbitrary load curve output

1.1.3 Switch box

The switch box is connected to each PV module. Usually three modules of the same type are connected in series through the switch boxes to a grid inverter. Normal grid connected operation is monitored besides the I-V-curve measurements.

The switch box is controlled with the PXI using the PXI-6509 board which activate the 24 VDC load relays through appropriate optocouplers. The optocouplers are located indoors next to signal relays, which are controlled together with the load relays in order to multiplex the PV-module power and voltage signal lines to the BOP and the LEM voltage transducer.

The signal relays have a response time of 9 ms and a duration of bounce of 1 ms (closing). The load relays have a response time of 15 ms and a duration of bounce of 7 ms. All switching actions will be followed by 50 ms waiting time to ensure proper connection before the following measurements.

Figure 3: Switch box: multiplexing of 39 modules one shortcut relay, two change circuit relays each (FINDER 62.33.9.024.4040), current sensor (Isabellenhuette/Bader BMN4P/10H R010 0.1%) used for normal operation monitoring

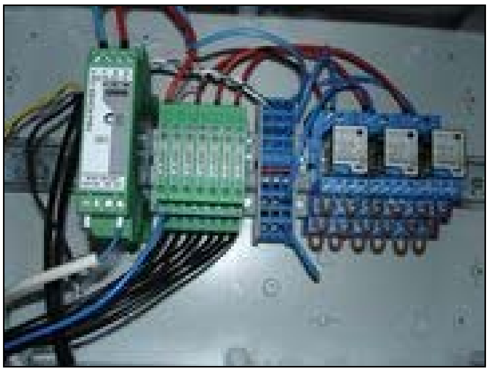

Figure 4: Optocouplers (green, Phoenix Contact PLC-OSP-5DC/300DC/1) and signal relays (blue, FINDER 55.34.9.024.5040). Installation shown for the control of three PV modules. At present time the extension to 39 modules is not finished yet (August 2006).

1.1.4 Reference test field

The PV modules are installed on the reference test field right above the control room, where the measurement equipment is located. The cable lengths do not exceed 25 meters. It is foreseen to measure I-V curves of PV modules, which are part of a 50 kW PV generator spread over other flat roofs of the building (Centre Hospitalier Emile Mayrisch CHEM, Esch/Alzette, Luxembourg). The signal and power lines will reach about 1000 meters. Large capacitive and inductive effects as well as noise introduced from the closer environment (elevators, climatic system, etc.) are expected. This measurement will be reported and published later.

Figure 5: Installation of three different PV modules: mono-Si, multi-layer a-Si and poly-Si

Figure 6: Connection of the switchboxes behind each PV module

1.2 Software

The complete test algorithm and data processing is programmed in LabVIEW V8.1 from National Instruments. This programming environment provides a broad range of mathematical functions, and interfaces to develop own formula or import MATLAB script nodes (in order to adapt sweep rates and form of load curves to the individual dynamic behaviour of each PV module type).

The codes of the programs, subroutines and algorithms can be requested from the authors. Executables, which can be driven on MS Windows 2000 and NT can be supplied by request only for non-commercial applications.

2 DEVELOPMENT OF THE TEST METHOD

2.1 Approach

The ranges of interests (I_{SC}, M_{PP}, V_{OC}) should be filled with as many measurement points as possible. The synchronous sampling to the load curve is done the way that the number of reading samples is a multiple of the number of the load curve samples. This means that the load curve is not a smooth analogue signal but a digitalised point-to-point curve. Although the slew rate of the Kepco is about 10 [V/µs] the number of set points has to be very well considered within the choice of function type (slopes, measurement time and sample rate) in order to avoid high steps between the single set points. The advantage of this method is a very accurate timing in synchronisation of measurements reading and load controlling. The average values of multiple measurements of the single setting points eliminate already noise without need of any physical filter. This reduces hardware development and costs and enables an observation and detection of other effects during the measurements.

2.2 Examples of arbitrary load profiles applied to a multi-layer a-Si PV-module with a slow dynamic response behaviour

Denomination of variables and constants:

$V(i)$ = load voltage at set point i

$i = 0, 1, 2, \ldots, n - 1$,

n = number of set points

Fs = sampling frequency [Hz]

V_{OFF} = negative offset voltage set at the BOP output in order to compensate the voltage drop @ I_{SC}

I_{SC} = short-circuit current

V_{OC} = Open circuit voltage of the PV module

The translation of the load profile curve to the load function frequency is given by the assignment of i into t:

$t = i*dt$, $dt = (n*f)^{-1}$ [s]

f= load sweep frequency [Hz]

2.2.1 Step function

$V(i) = V_{const}$

Large transient effects with a relative long duration can be observed, if bigger voltage steps (> 1 [V]) are applied. A detailed characterisation of this effect is not subject of this study. But it is of interest to know exactly the conditions in the measurement system. This will be examined within the following measurement campaigns

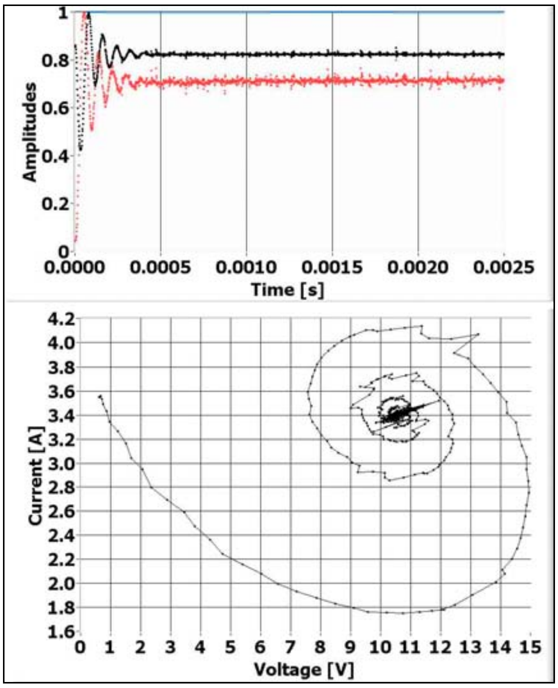

Figure 7: step load 0 V to 10 V step, PVcurrent (**black**), PV voltage (**red**) amplitudes normalised. Load function sweep 400[Hz], 2ksamples @ 800[kHz], Large transient response signal duration about 0.25 [ms].

2.2.2 Linear function

$V(i) = V_{OC}*i + V_{OFF}$

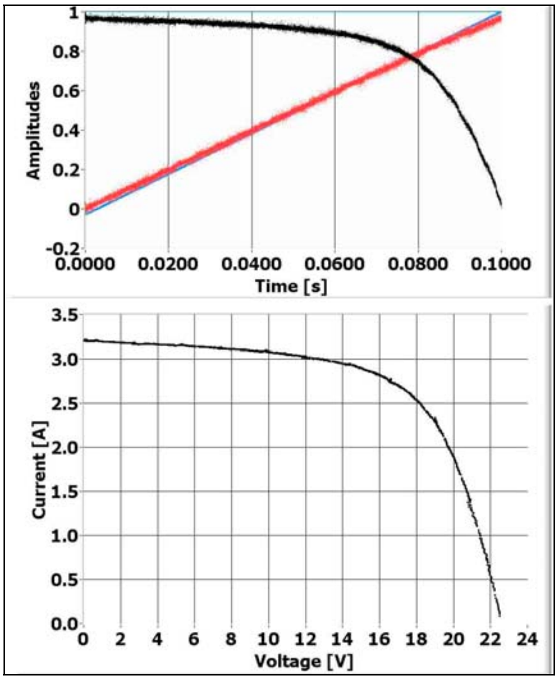

Figure 8: PV current (**black**), PV voltage (**red**) and load voltage (**blue**) amplitudes normalised. Linear load function sweep 10[Hz], 80ksamples @ 800[kHz], I-V-curve averages 80 samples/load point.

2.2.3 Sinusoidal function

$V(i) = V_{OC}*\sin(phase(i)) + V_{OFF}$

$phase(i) = -\pi/2+f*2*\pi* i/Fs$

The sinusoidal function provides forward-backward measurements with smooth change of direction. This function is suitable to discover the dynamic limits within a few iterations. Figure 9 shows a strong hysteresis between the measurement directions. In figure 10 no hysteresis is detectable.

A similar behaviour but not of the same intense was observed within the measurements of the monocrystalline PV module.The polycrystalline PV module showed almost no remarkable hysteresis effects within the same load sweep rates.

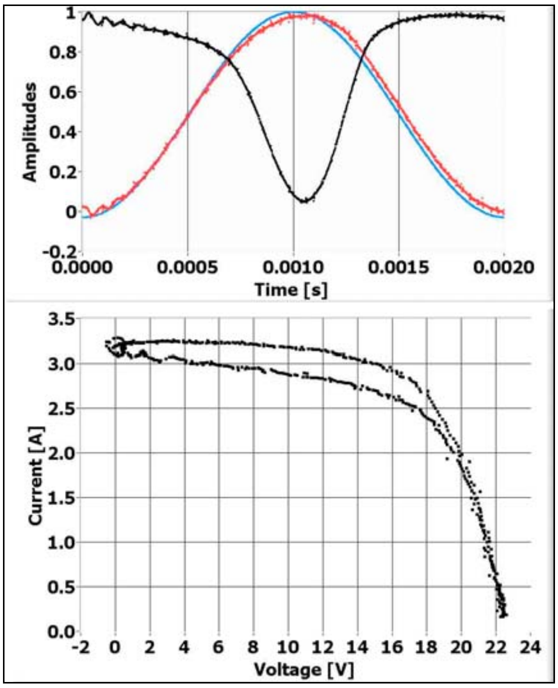

Figure 9: PV current (**black**), PV voltage (**red**) and load voltage (**blue**) amplitudes normalised. Sinusoidal load function sweep with 1 oscillation @ 500[Hz], 400 samples @ 800[kHz], I-V-curve averages 4 samples/load point.

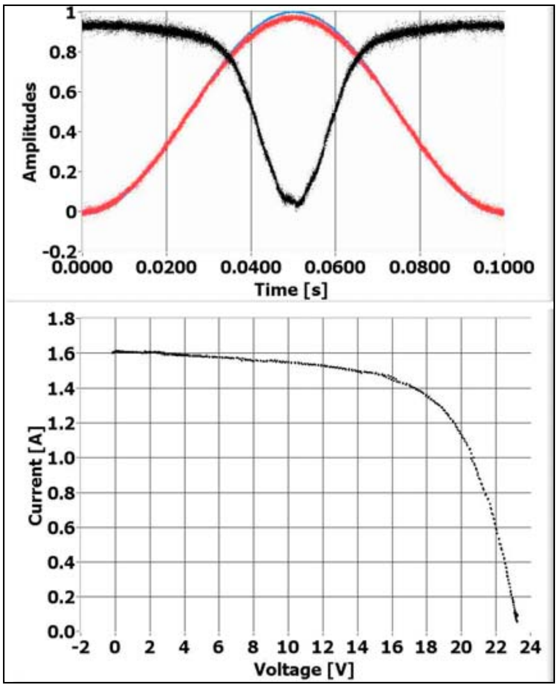

Figure 10: PV current (**black**), PV voltage (**red**) and load voltage (**blue**) amplitudes normalised. Sinusoidal load function sweep 1 oscillation 10[Hz], 400 samples @ 800[kHz], I-V-curve averages 200 samples/load point.

Natural logarithmic function

$V(i) = V_{off}+V_{OC}*\ln(V_{OC}*\tau^3*(m*\tau)^p+1)/\ln(V_{OC}*(m*\tau)^p+1)$

$\tau = i*n^{-1}$, from $\tau_0 = 0$ to $\tau_n = 1$

m = logarithmic constant

p = exponential constant

The shape of this logarithmic function seems to be optimal to measure PV modules with steep slopes. It is variable in slope and curvature due to the values of the logarithmic and exponential constant. The multi-layer amorphous silicon PV module showed some harmonic transient signals in the part of almost constant voltage slope.

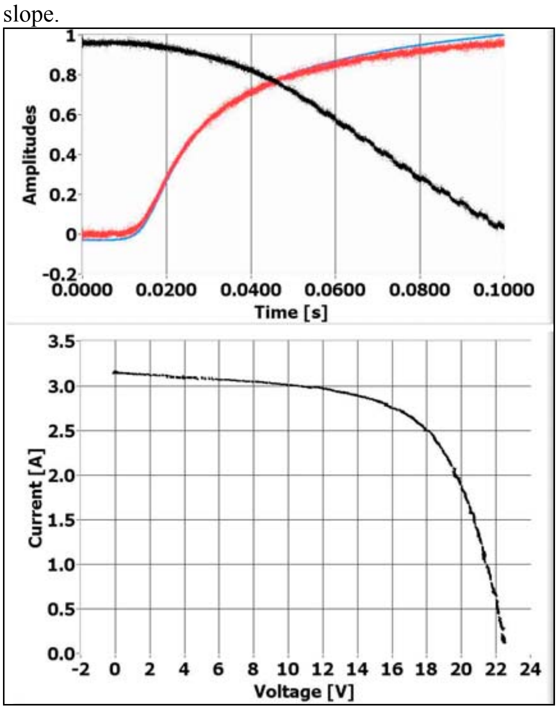

Figure 11: PV current (**black**), PV voltage (**red**) and load voltage (**blue**) amplitudes normalised. Natural logarithmic load function (p=5, m=10) sweep @ 10[Hz], 1ksamples @ 800[kHz], I-V-curve averages 80 samples/load point.

3 RESULTS

At some points there were problems expected, but they did not carry too much weight with the first three devices under test:

- I-V-curve measurements were performed without proper shield connections.
- The noise reduction potential is not completely utilised.
- Wiring capacities and inductances are not negligible over the installed lengths of about 25 meters.
- PV power line connection star-shaped multiplexed with distributed switch boxes.

The first experimental measurements with the different silicon PV modules , lead to following results:

- The load function shape, which gave the measurement signals of the best quality is the sinusoidal load function.
- The load sweep rate of 10[Hz] is appropriate for all three modules. The overall measurement delay (including switching and setting of V_{OFF} and V_{OC}) between to devices under test lies at 0.4 seconds.

4 CONCLUSIONS

Outdoor I-V-curve measurements do not require such a dynamic as measurements under pulsed solar simulators with stable illumination for 2 [ms] to 30 [ms]. A well balanced dynamic combined with an adapted shape of the load curve can serve most constraints, namely the large number of devices under test, noise in the measurement signals and the dynamic of environment conditions. The first measurement campaign is used to demonstrate the functionality of the test facility with common silicon PV modules. After the installation of the remaining test points in the reference test field, it will be ready to test other types of PV modules with unspecified response behaviour due to dynamic load changes.

Furthermore the I-V test facility can be used without modifications for measurements with fast response dynamics under pulsed solar simulators.

Please, visit the CRTE website for further information and follow up the installation and operation of PV-Lab: www.crte.lu

5 References

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