Innovative and Simple PV Generator Procedure to test PV Inverter according to EN 50530 Standard Static MPPT Efficiency

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Abstract- This paper details the different steps of an innovative and simple PV generator emulator (PVE) test method used to emulate the PV generator behavior required to carry out EN 50530 European standard static MPPT efficiency test for a given PV inverter (PVI). The developed test procedure accurately determines the PVE control parameters using data selected from the datasheet of the PVI which is the Equipment Under Test (EUT) and basing on the EN 50530 standard requirements. A software implemented under LabVIEW environment allows one to automatically compute the required test parameters, to communicate them to a STM32F4 target in order to accurately control the PVE for a given test scenario and to display the emulated I-V and P-V characteristics. Simulations carried out under the PSIM software demonstrate the accuracy of the suggested test procedure to fulfill the EN 50530 requirements. Furthermore, experimental tests, carried out for the case study of a real-world 1100 W PVI, validate the effectiveness of the developed test procedure, and facilitate a new approach to the EN 50530 MPPT efficiency test goals.

Keywords PV generator Emulator (PVE); PV inverter (PVI); EN 50530 standard; static MPPT efficiency test procedure; LabVIEW Graphical User Interface; experimental investigations.

1. Introduction

Nowadays, solar renewable energy is among the best solutions to feed different applications, such as grid tie-in systems, and to ensure remote regions electrification [1-3]. This is mainly due to the growth of the photovoltaic market engendered by the constant decline in the PV installation cost as well as for environmentally friendly and socio-economic reasons. The validation of the PV systems' components is necessary to ensure safe and efficient operation of PV installations. Inverter is the key power component of a PV system stage [4]. It performs DC to AC power conversion in addition to MPPT control. Therefore, focusing on PVI operation is a mandatory issue, and conformity to standards is primordial for PV systems. Besides that, standards study a multitude of conformity aspects by proposing tests and platforms that allow estimating the profitability of a PVI in a PV system and predicting the evolution of its effectiveness. Among these conformity aspects, the security, such as anti-islanding protection [5], and the performance such as efficiency [6] can be cited. The performance of a PVI is closely linked to the DC power generation. Indeed, a PVI reaches the maximum of its efficiency when its DC input corresponds to the maximum power point (MPP). Generally, manufacturer datasheets succinctly provide the Maximum PVI conversion efficiency or the European one, while the overall PVI efficiency is the most accurate and significant PVI efficiency to be taken into consideration. The overall PVI efficiency includes the efficiency of the MPPT, static and dynamic, and also that of the power conversion stage [7]. The EN 50530 standard titled "Overall efficiency of grid-connected photovoltaic inverters" [8] introduces a testing procedure to evaluate grid-tie PVIs and provides three kinds of efficiency tests: a Static MPPT efficiency test, a Dynamic MPPT efficiency test and a Conversion efficiency test. According to this standard, the PVI, designated as the EUT, can be supplied by a PVE, which in turn, plays the PV generator role and is able to vary the DC power at the EUT input as required by the EN 50530 standard tests. In fact, the emulators are often used in performance evaluation tests as well as in prototyping stage. So the equipment can be pushed to work under boundary conditions or reproduce faulty scenarios without damaging the generator. So, several research works are focused on the PVE and especially on the use of a PVE for testing PVIs have been reported. Among these research papers, we can cite [7] and [9-11]. Researchers in [7] presented a PVI test bench to evaluate the efficiency of the maximum power point tracking (MPPT) control using PV array simulation. The tested equipment was a 500 kW PVI and the tests included both static and dynamic MPPT efficiencies. In [9], an experimental setup was presented for testing PVIs, evaluating their conversion efficiency and analyzing their harmonic contents. Authors in [10] presented a PVE to test commercial and prototyped grid–connected PVIs. The developed PVE was based on dSPACE - interface, which facilitates parameters modification and online supervision of the output results. The PV emulator was evaluated for the case of a resistive load and grid-tie PVI. As for the platform, it also provides the possibility to test MPPT algorithms under different shading profiles. Research works in [11] presented the validation of a high- accuracy PV array emulator. This emulator was designed by using only data provided by a PV panel datasheet and was used to test the MPPT algorithm's efficiency and power energy conversion performances of commercial PVIs.

Three main aspects of PVE systems have been addressed by researchers [12-13], namely the PV model [14-17], the control strategy [18-21] and the power converter [22-27]. Furthermore, several authors have dealt with the EN 50530 standard efficiency issue [28-35]. In [28], the authors evaluated the performance of two technologies of PV cells, namely multi crystalline silicon cSi and thin-film PV TF, under various fluctuation profiles of the irradiance specified by EN 50530 standard procedure. In [29], a new adaptive neural control-based strategy for MPPT was proposed and compared to the "Perturb and Observe" (P&O) algorithm. Then, an experimental test set-up was designed to evaluate the control approach under the irradiance profiles in accordance with the EN 50530 standard. In order to investigate the suitability of the EN 50530 standard European efficiency, the authors in [30] developed experimental tests for four different inverters. In [31], a dynamic 10 kVA PVE implementation was described and discussed in order to reproduce PV generator behaviour for the MPPT performance test of PVIs. A GUI associated to the proposed PVE includes, among other possibilities, both the static and the dynamic efficiencies tests while following the EN 50530 standard. In [32], micro-inverters were evaluated according to the proposed procedure defined in the EN 50530 standard. Results for two micro-inverters were compared to string inverters. Research paper [33] offers a self-adaptive maximum power harvesting technique for a PV array, using Takagi-Sugeno-Kang Fuzzy Logic Control (TSKFLC). The effectiveness of the proposed TSKFLC was tested under EN 50530 standard conditions by simulation performed under MATLAB/Simulink and by control implementation on an experimental test bed.

Recently, research works like [34] and [35] have provided a novel formulated P&O methodology for the PVI MPPT control. Compared to the classic P&O approach, its improved and adaptive versions give results respecting the EN 50530 standard shading patterns while showing the efficiency of the new P&O proposed control method. Similarly, in [35], authors suggested an improved evolutionary programming MPPT approach that complies with the requirements of the EN 50530 standard. This approach was evaluated under MATLAB/Simulink simulation then tested experimentally.

The work discussed in this paper began during a research project, developed in collaboration with the Tunisian Ministry of Industry and Small and Medium Enterprises. The aim of this research was to provide an experimental platform dedicated to the test of grid-tie PVIs. This work is still under development within a on-going project funded in part by PAQ-Collabora (PAR&I-Tk) program, which seeks to design and implement a original and innovative benchmark for research works and training to look for PHIL principle-based New Energy Technologies (NeTE).

In accordance with a considered literature review, there is no research studies that have detailed and treated the test procedure that describes how the necessary PV generator characteristics are defined according to the different scenarios required by the EN 50530 standard. This paper provides an innovative and simple PVE procedure based on this standard. The steps of this proposed procedure are detailed and the analytic formulas used to reproduce the PV behavior are presented. After, the proposed PV test procedure is validated on a developed low-cost PVE-based platform including an ergonomic Graphical User Interface (GUI), developed under LabVIEW software, which enables the automation of the efficiency test procedure according to the EN 50530 standard. The paper is constructed as follows. Section 2 underlines a concise overview of the EN 50530 standard requirements. Section 3 details the proposed PV generator test procedure for EN 50530 Standard Static MPPT Efficiency and highlights simulation results that validate the procedure test concept. Section 4 shows the experimental results supporting the high accuracy of the developed test procedure. Finally, conclusions and prospects are summarized in Section 5.

2. EN 50530 Standard guideline for the static MPPT efficiency test

The EN 50530 standard is addressed to a procedure allowing the measurement and computing of the grid-tie PVIs overall efficiency in order to assess the PVIs effective power. The presented procedure details the computing methodologies of: 1) the MPPT efficiency, 2) the Conversion efficiency, and 3) the overall efficiency. The MPPT efficiency is based on two efficiencies, which are the Static and the Dynamic MPPT efficiencies. Additionally, referring to the subsection A.1.2 of the A appendix of the EN 50530 standard dealing with the static characteristic requirements, it stipulates that the PVE real characteristic P-V must not diverge more than 1% of the power in the voltage interval [0,9.$U_{MPP,PVE}$, 1,1.$U_{MPP,PVE}$ related to the predetermined characteristic at the standard required conditions. $U_{MPP,PVE}$ refers to the MPP voltage reproduced by the PVE [8]. In this instance, the efficiency tests' performance involves additional procedures to be determined clearly and precisely. This paper presents a new simple test approach implemented to fulfill the EN 50530 standard requirements and then to evaluate the PVIs Static MPPT efficiencies. Moreover, the standard imposes the PV model equations and the requirements associated to the evaluation of the PVI static MPPT efficiency. These various test scenarios are depicted in Table 1. They address the PV generator technology, the power ratios of the PVE MPP power $P_{MPP,PVE}$ and the PVI rated input power $P_{DC,r}$, as well as related MPP voltages. Considering these requirements, the proposed test procedure is hence detailed to allow reproducing the I-V characteristics required by the scenarios of the PVI performance tests.

3. Proposed methodology and simulation results

This section first describes the proposed PVE test procedure to fulfill the conditions of the proposed scenarios as specified in the EN 50530 standard. Second, it presents the simulations results that illustrate the proposed procedure's accuracy and performance.

Table 1. Specified EN 50530 static MPPT efficiency test conditions [8]

PVE I-V curve technology				***PVE MPPT voltage level*** *[V]*				
cSi technology				$V_{MPP,max}$ *(or 0,8.*$V_{DC,max}$*)*				
				$V_{DC,r}$				
				$V_{MPP,min}$				
TF technology				$V_{MPP,max}$ *(or 0,7.*$V_{DC,max}$*)*				
				$V_{DC,r}$				
				$V_{MPP,min}$				
Power Ratio: $P_{MPP,PVE}/P_{DC,r}$ ***×100% [%]***	***5***	***10***	***20***	***25***	***30***	***50***	***75***	***100***

2.1. Proposed PVE test procedure

The proposed procedure consists of accurately determining the parameters that allow the PVE to reproduce the performance of a real PV generator while fitting the EN 50530 standard's requirements. To do this, a software framework has been designed and implemented. It includes:

➢ Software designed under the LabVIEW environment, which consists in: i) Graphical User Interface (GUI) allowing the user to communicate the parameters extracted from the EUT datasheet as well as the instructions required to execute the PVE's control algorithm via a *Configuration panel* and to display the PVE I-V and P-V characteristics via a *Results panel* ii) Code developed to compute the variables required to control the PVE.

➢ Software designed and implemented on a STM32F4 target to control the PVE for generating the required power starting from the control parameters communicated from the LabVIEW environment via a serial protocol.

In fact, unlike several researches such as those presented in [15], which are based on LabVIEW program for PVE the control implementation we have developed a LabVIEW code for sending instructions useful for the standard tests and also for displaying the resulting PVE curves. Thus, this code includes a GUI allowing to automate the EN 50530 standard scenarios. The PVE control is implemented on a low-cost microcontroller and can be completely independent of this interface. Fig. 1 depicts the *Configuration panel* and the *Results panel* of the GUI developed under the LabVIEW environment.

The PVE test procedure steps followed to reproduce EN 50530 standard's test scenarios are described as follows. First, the user enters the PVI data via the graphical interface developed under LabVIEW. This data, provided in the datasheet of the PVI to be evaluated, are the DC rated power $P_{DC,r}$, the DC input rated voltage $V_{DC,r}$, and the minimum and the maximum MPP voltages, V_{MPPmin} and V_{MPPmax}, respectively. According to the EN 50530 standard requirements that provide the PV model formulas to follow and indicate the PVI datasheet parameters to be considered, the code developed under LabVIEW computes the parameters $V_{oc,STC}$, $I_{sc,STC}$, I_{MPP} and G by using equations (1), (2), (3) and (4),. Indeed, these variables are defined from formulas that depend on the PVI parameters and allow one to reach a margin of error at less than 1% of $P_{MPP,PVE}$, as requested by the standard.

$$V_{oc,STC} = \frac{V_{oc}}{(1+\beta(T_{PV}-T_{STC}))(ln\left(\frac{G}{C_G}+1\right)C_V - C_R G)} \quad (1)$$

$$I_{sc,STC} = \frac{I_{sc}}{(1+\alpha(T_{PV}-T_{STC}))}\frac{G_{STC}}{G} \quad (2)$$

$$I_{MPP} = \frac{P_{MPP}}{V_{MPP}} \quad (3)$$

$$G = ratio\,.K \quad (4)$$

$V_{oc,STC}$: Open-Circuit voltage in STC conditions [V]

$I_{sc,STC}$: Short-Circuit current in STC conditions [A]

V_{oc} : Open-Circuit voltage in STC conditions [V]

I_{sc} : Short-Circuit current under operating conditions [A]

β : Voltage temperature coefficient [%/°C]

α : Current temperature coefficient [%/°C]

G : Irradiation in operating condition [W/m²]s

G_{STC} : Irradiation in STC conditions (1000W/m²)

C_V, C_G, C_r : Correction Factors depending on panel technologies [ ],[W/m²],[m²/W]

T_{PV} : Temperature of PV module [°C]

T_{STC} : Temperature in STC conditions (25°C)

V_{MPP} : MPP PV generator voltage [V]

I_{MPP} : MPP PV generator current [A]

P_{MPP} : MPP PV generator power [W]

$ratio$: Power ratio according to EN 50530 test scenario [ ]

K : Constant [W/m²]

Voc and Isc are computed by using respectivelyV_{MPP}, FF_UandI_{MPP}, FF_I.From these equations (1) (2) (3) and (4), one can deduce the PV generator characteristics that allow the PVE to reproduce the required PVI DC input power according to EN 50530 test scenario. Moreover, the EN 50530 standard requires the PV model to be used. The equation (5) describes the I-V relationship.

$$I_{PV} = I_{SC} - I_0\left[\left(e^{\frac{V_{PV}}{V_{OC}.C_{AQ}}}\right)-1\right] \quad (5)$$

I_{PV} : PV generator current under operating conditions [A]

I_0 : Saturation current of the diode [A]

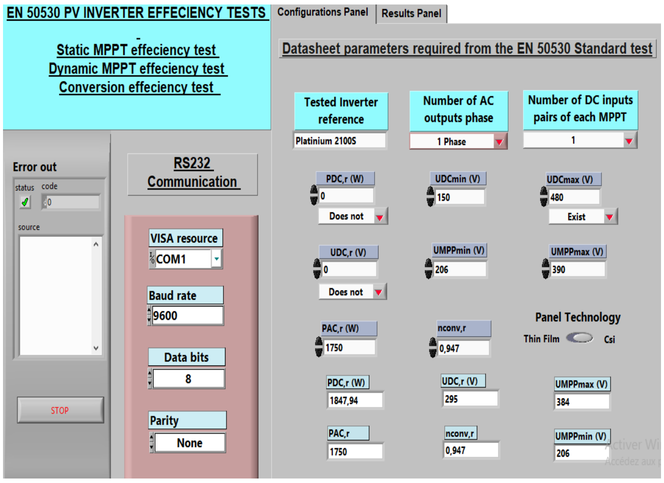
V_{PV} : PV generator voltage under operating conditions [V]

C_{AQ} : Constant depending on current and voltage fill factors [--]

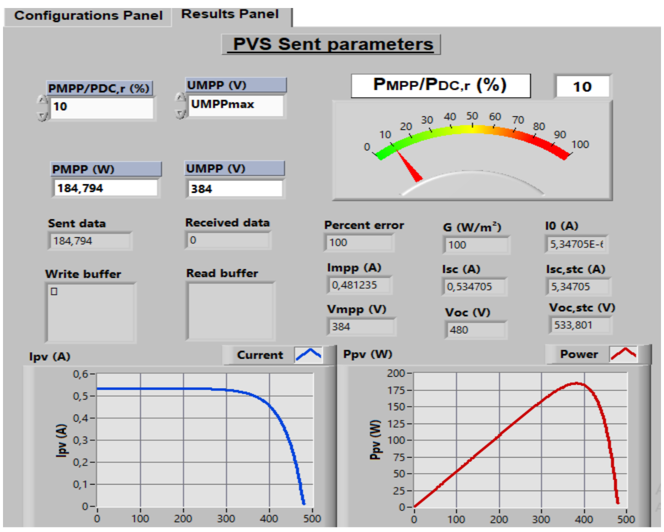
FF_U : Voltage fill factor [--]

FF_I : Current fill factor [--]

Indeed, considering accurate Look-up tables, previously reported in [36] to reproduce I-V curves at any climatic conditions, the required I_{PV} is computed in line following the steps and formulas delivered by the EN 50530 standard. In addition, the I_{PV} computation time is strongly optimized due to the digital device in question.Table *2* features the main assets of our proposed approach compared to other works based on the Look-up table implementation [12]. For this purpose, Look-up table 1 allows computing the voltage $V_{oc,STC}$ without having to use the logarithmic expression of the equation (1) and Look-up table 2 allows computing the current I_{PV} without having to use the exponential expression of the equation (5).



(a) Configuration panel



(b) Results panel

Fig. 1. Graphical User Interface developed under the LabVIEW environment

Table 2. Simulation conditions for the EN 50530 test scenarios

<table>
<tr><th></th><th colspan="2">Variable</th><th>Online G/T change</th><th>Points</th><th>Independence</th><th>Controller</th></tr>
<tr><td>Look-up table 1</td><td colspan="2">$I_{PV} = f(V_{PV})$</td><td>G/T</td><td>3001</td><td>-Climatic conditions
-Panel parameters</td><td rowspan="2">Microcontroller STM32F4 discovery</td></tr>
<tr><td>Look-up table 2</td><td colspan="2">$V_{OC} = f(G)$</td><td>G/T</td><td>1501</td><td>-Climatic conditions
-Panel parameters</td></tr>
<tr><td></td><td colspan="2">Memory</td><td colspan="3">Accuracy</td><td>Adaptability</td></tr>
<tr><td>Look-up table approach</td><td colspan="2">Memory used
(18 kbytes/1Mbytes Flash) → 1,8% of the memory resources</td><td colspan="3">High accurate
<1% of error for 96% of the I-V curve</td><td>-G/T independence
-Flexible for Panel parameters changes</td></tr>
</table>

Fig. 2 highlights the proposed PVE-based platform and the communication between its components. Fig. 3 presents the flowchart of the proposed test procedure.

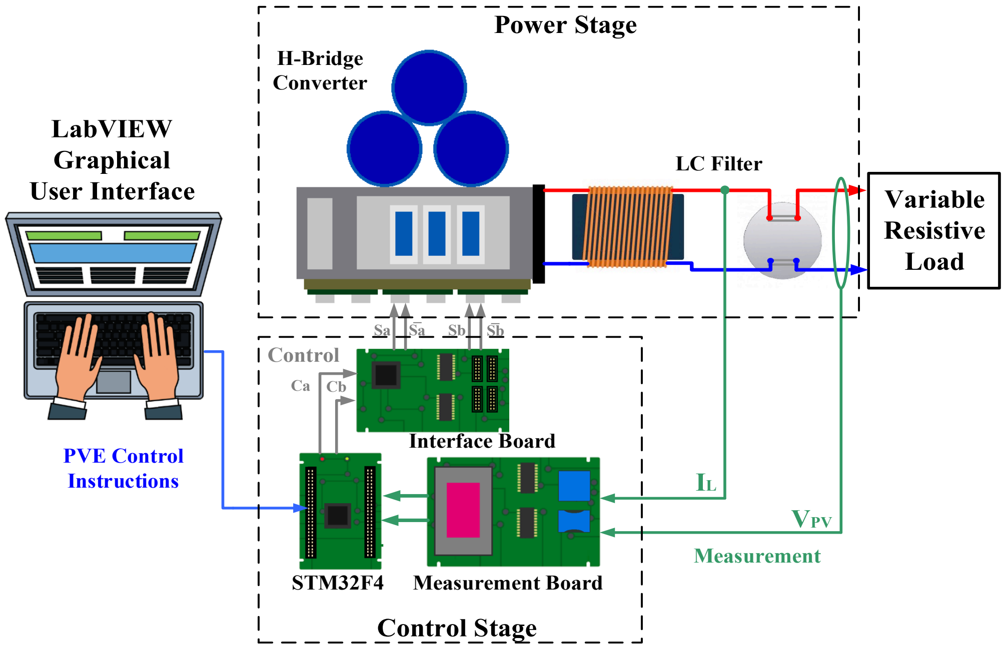


Fig. 2. Proposed PVE-based platform and the communication between its components

3.2 Simulation Results

Simulations have been carried out under PSIM software of POWERSIM to prove the performance of the proposed approach. Detailed simulation results were previously presented in [38] for the case study of the PLATINIUM 2100S PVI to support the high accuracy of the PVE's characteristics. In this paper, the ENFINITY 1100 TL PVI [37] is chosen as the EUT to verify that the proposed test procedure allows to reproduce all the operating points required by the EN 50530 standard to generate the PVE's I-V and P-V characteristics for the computation of the static MPPT efficiency of the EUT. The values the needed parameters are taken out from the EUT datasheet [37], and/or computed according to the EN 50530 standard formulas announced in its C appendix [8]. The variables $V_{OC,STC}$ and $I_{SC,STC}$ were computed using both the proposed GUI and the

Table 3 details the simulation conditions.
For the ENFINITY 1100 TL PVI case study, the results

code developed under the LabVIEW environment. For the ENFINITY 1100 TL PVI case study, the results
highlight the accuracy and efficiency of the proposed approach for each power ratio scenario required by the EN 50530 standard. Fig. 4 depicts the I-V and P-V characteristics under the previously mentioned conditions. Moreover, one can notice that the percent relative errors between the reference powers and those resulting from the simulated I-V curves, according to equation (1), are less than 0,003% as presented in Table ***4***. This result proves the accuracy of the PVE's control and characteristics for fulfilling the EN 50530 standard requirement which admits up to a power error of 1%

$$\varepsilon_{P_{\%}} = \frac{ReferenceP_{MPP,PVE} - SimulatedP_{MPP,PVE}}{ReferenceP_{MPP,PVE}} . 100\% \qquad (6)$$

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Table 3. Simulation conditions for the EN 50530 test scenarios

cSi Technology-based PVI Enfinity 1000 TL **$P_{DC,R}$= 1100 W , T=25 °C, V_{MPPmin} = 120 V, $I_{SC,STC}$ = 10,185 A**			
Ratio [%]	**G [W/m²]**	**$P_{MPP,PVE}$ [W]**	**$V_{OC,STC}$ [V]**
5	50	55	177,496
10	100	110	166,813
20	200	220	158,246
25	250	275	155,986
30	300	330	154,344
40	400	440	152,177
50	500	550	150,907
75	750	825	149,756
100	1000	1100	150,128

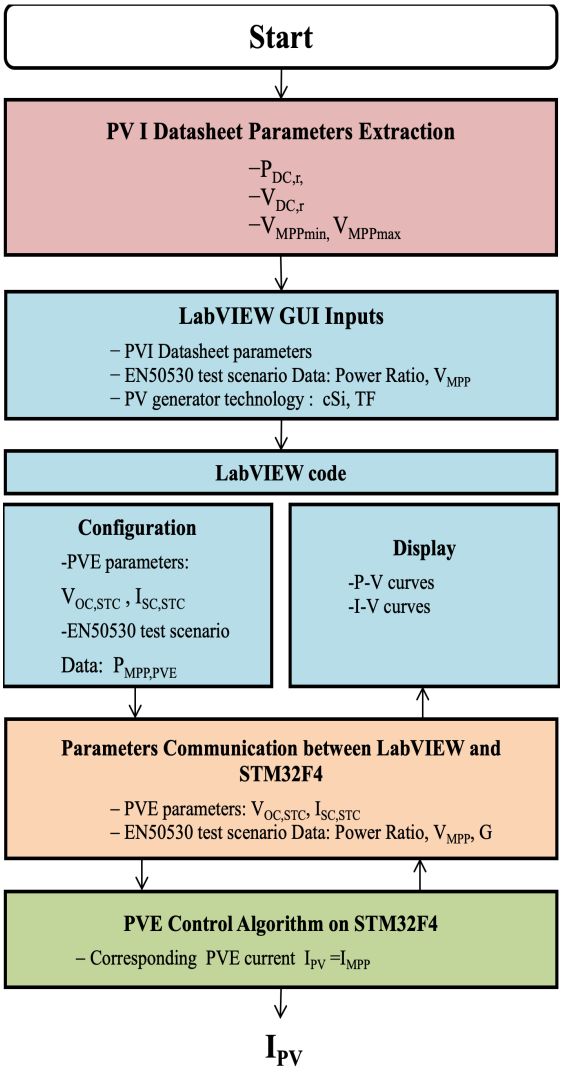

Fig. 3. The proposed test procedure steps flowchart.

Table 4. Computed and simulated PVE powers percent relative error

Ratio [%]	Computed $P_{MPP,PVE}$ [W]	Simulated $P_{MPP,PVE}$ [W]	$\varepsilon_{P\%}$ [%]
5	55	55,002	0,003%
10	110	110,004	0,003%
20	220	220,008	0,003%
25	275	275,010	0,003%
30	330	3300,011	0,003%
40	440	440,015	0,003%
50	550	550,019	0,003%
75	825	825.030	0,003%
100	1100	1100,043	0,003%

4. Experimental Investigation

4.1 Experimental setup validation

To validate the proposed test procedure, an experimental platform was designed and installed at the laboratory. The final aim of this test bench is to ensure the test of the overall efficiency of a given PVI under test [38]. The experiment set-up consists of a 6 kVA PVE, an interface board that achieves an adapted voltage level for the PVI switching signals and a sensor board equipped with current and voltage sensors. These components have been designed and developed in the QehnA research team of L.S.E laboratory The PVE's control algorithm implementation has been performed using a low-cost digital solution. Indeed, it is based on the STM32F4 digital device. The I_{PV} current is computed using an accurate Look-up tables [36], as detailed in Section 3.

The PVE power structure is based on two converters; a three-phase diode rectifier and a H-bridge DC/DC converter, interfaced by a DC link capacitor filter. A LC filter is designed to minimize voltage and current ripples at the DC/DC converter output. A variable resistive load is used to sweep different operating points of the I-V characteristic. The PVE receives reference parameters from the GUI.

The GUI computes these reference parameters using PVI parameters given by datasheet. The PVE, according to these references reproduces the required opertating points based on the developped controls. The considered test-bed is shown in Fig. 5 and its main characteristics are summarized in Table 5.

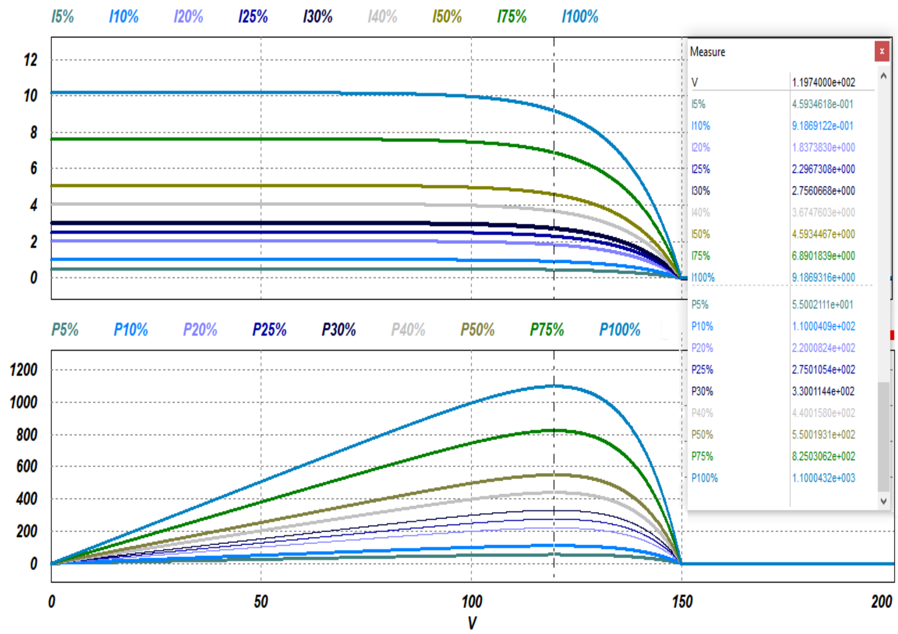

Fig.4. I-V and P-V simulated characteristics for the ENFINITY 100 TL PVI under the EN 50530 standard conditions.

Table 5. The characteristics of the designed PVE

Component	Characteristics
Three-phase transformer	6 kVA, m = 2,6
Three-phase autotransformer	6 kVA
Three-phase diode rectifier	SKD 51/16, 1700 V-50 A
H-bridge DC/DC converter	SKM50GB1 2T4, 1200 V, 50 A
L C filter	L=60 mH, C=180 µF
Adjustable resistive load	Up to 2,5 kW
Digital storage oscilloscope	MCP DQ8074, 70 MHz, 2 GSa/s

4.2 Proposed procedure

The proposed PVE's structure has been validated for different test conditions. Detailed results, proving the PVE required accuracy, have been presented in [35] and [37]. In this paper, more complete tests were carried out to cover all the PVE's operating points as required by the EN 50530 standard. In a first step, since V_{OC} and I_{SC} characteristics are the most critical points for a given I-V curve, experimental tests were performed to define these two crucial points. Fig. 6 and Fig. 7 underline the obtained voltage and current outputs of the experimental PVE respectively, in the open-circuit and the short-circuit conditions.

Notice that Channel 2 represents I_{PV} and Channel 3 represents V_{PV}. These tests have been performed for V_{OC}=150,128 V and I_{SC}=10,185 A, under STC temperature and irradiance conditions. One can notice that the percent relative errors between the real PV generator measurements and the emulated outputs are lower than the maximum tolerated value 1%.

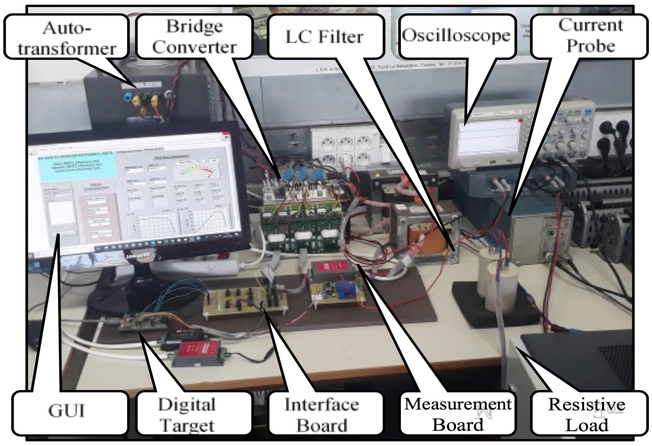

Fig.5. Experimental PVE setup to evaluate the EN 50530 static MPPT efficiency

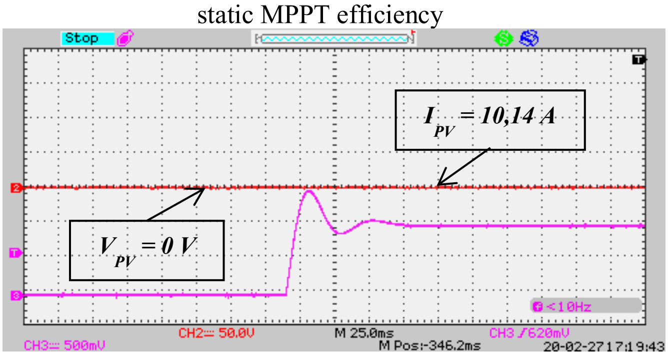

Fig 6. PVE outputs in Short-circuit operating conditions under T=25 °C and G=100 W/m².

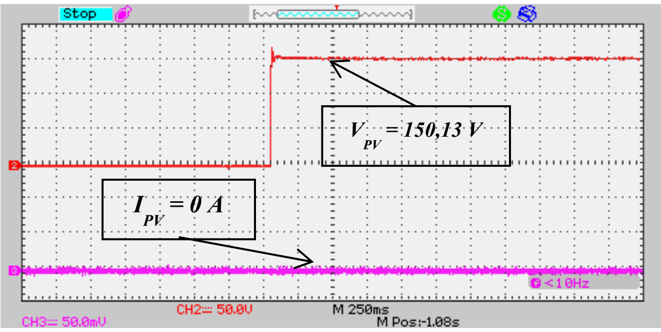

Fig. 7. PVE outputs in Open-circuit operating conditions under T=25 °C and G=100 W/m².

In a second step, the developed test procedure has been tested in experiments according to the required static MPPT efficiency test conditions. To carry out these experiments, an accurate resistive load is supplied by the PVE for the different power ratios. ***Error! Not a valid bookmark self-reference.*** presents the experimental conditions required by the EN 50530 standard test scenarios. Indeed, the required power ratios were achieved for $P_{DC,R}$ =1100 W and V_{MPPmin} =120 V. These data are the computed value by the proposed test procedure. They were the references that we need to reach.

Table 6. Experimental conditions for the EN 50530 test scenarios

cSi Technology-based PVI Enfinity 1000 TL $P_{DC,r}$= 1100 W , V_{MPPmin} = 120 V, $I_{SC,STC}$ = 10,185 A					
Ratio [%]	**G [W/M²]**	$P_{MPP,PVE}$ **[W]**	I_{MPP} **[A]**	$V_{OC,STC}$ **[V]**	**R [Ω]**
5	50	55	0,458	177,496	261,82
10	100	110	0,917	166,813	130,91
20	200	220	1,833	158,246	65,45
25	250	275	2,292	155,986	52,36
30	300	330	2,750	154,344	43,64
40	400	440	3,667	152,177	32,73
50	500	550	4,583	150,907	26,18
75	750	825	6,875	149,756	17,45
100	1000	1100	9,167	150,128	13,09

Fig. 8, Fig. 9 and Fig. 10 display the obtained experimental results for three different power ratio test conditions, namely 5%, 50% and 100%, respectively. The PVE current and voltage waveforms are recorded in both transient and steady states to highlight the dynamic behavior of the PVE and the accuracy with which the PVE current and voltage outputs reach the reference values.

Fig. 11 depicts all the nine P-V curves generated experimentally by the PVE for all the power ratios dictated by the EN 50530 standard for the MPPT efficiency tests. The obtained curves are displayed on the *Results panel* of the developed GUI under the LabVIEW environment (Fig. 1).

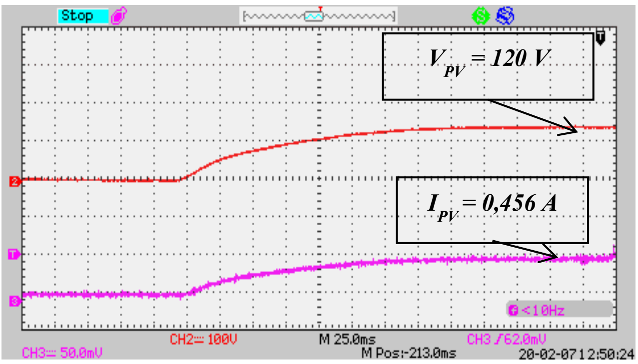

Fig.8. PVE voltage and current outputs for 5% of $P_{DC,r}$ under T°=25 °C and G=50 W/m².

To highlight the accuracy of the PVE's outputs to fulfill the conditions necessary to carry out PVI efficiency tests, percent relative errors have been computed according to equation (7).

$$\varepsilon_{X_{\%}} = \left|\frac{X_{PV} - X_{PVE}}{X_{PV}}\right| . 100\%$$

X is the current, voltage or power variable, X_{PVE} is the measured PVE's current, voltage or power output.

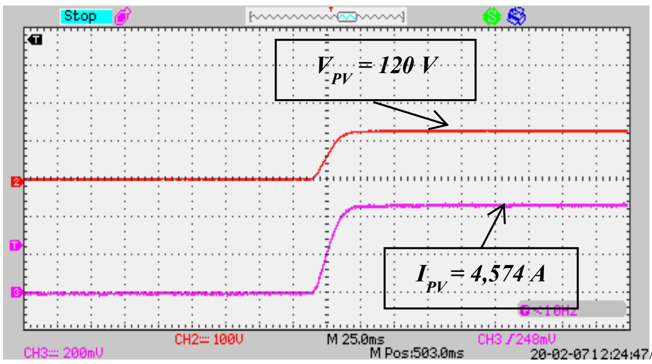

Fig. 9. PVE voltage and current outputs for 50% of $P_{DC,r}$ under T°=25 °C and G=500 W/m².

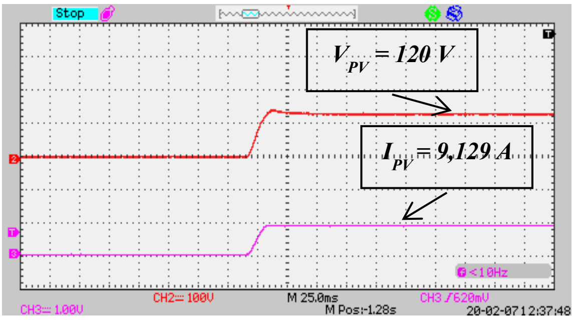

Fig. 10. PVE voltage and current outputs for 100% of $P_{DC,r}$ under T°=25 °C and G=1000 W/m².

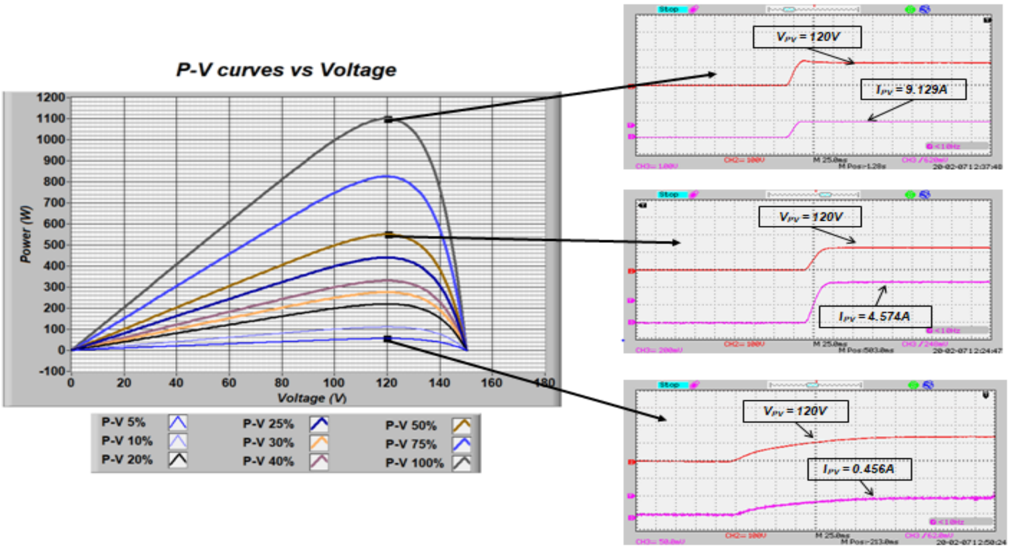

Fig. 11. Experimental emulated P-V characteristics.

Table 7 details the results obtained for all the EN 50530 standard's required test conditions. These results are compared to their references shown in Table .6 and percent errors are computed for all the power values. Fig. 12 illustrates the power percent relative errors obtained for all power ratios required for the EN 50530 test conditions. In fact, The deviation between the experimental data and the theoretical ones results from the cumulated error value of the control approach, algorithm implementation such as sampling time and variable format as well as measurement devices precision. One can notice that these errors are much smaller than ± 1%, which is the error margin tolerated by the EN 50530 Standard in PV generation steady state conditions. The obtained results strongly validate the PVE's performances in terms of the required power percent relative errors for all the power ratios as well as the extreme operating conditions. Then, these results facilitated a way to achieve the efficiency testing in accordance with the EN 50530 standard.

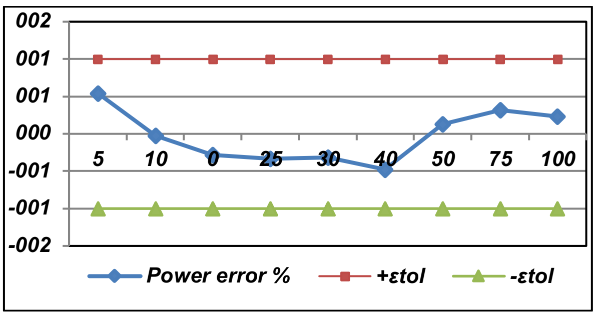

Fig. 12. Power percent relative errors obtained for all power ratios required for the EN 50530 efficiency test conditions.

Table 7. Percent relative error between theoretical and experimental results

Ratio [%]	Reference Power $P_{MPP,PVS}$ [W]	Reference Voltage $V_{MPP,PVS}$ [V]	Measured Voltage V_{MPPmin} [V]	$\varepsilon_{V_{\%}}$ [%]	Reference Current $I_{MPP,PVS}$ [A]	Measured Current $I_{MPP,PVE}$ [A]	$\varepsilon_{I_{\%}}$ [%]	Measured Power $P_{MPP,PVE}$ [W]	$\varepsilon_{P_{\%}}$ [%]
5	55	120	119,969	0,03	0,458	0,456	0,51	54,701	0,54

10	110	120	119,866	0,11	0,917	0,918	0,15	110,031	0,03
20	220	120	119,710	0,24	1,833	1,843	0,52	220,625	0,29
25	275	120	120,654	0,54	2,292	2,287	0,20	275,926	0,34
30	330	120	120,124	0,10	2,750	2,756	0,22	331,050	0,32
40	440	120	120,208	0,16	3,667	3,678	0,30	442,095	0,48
50	550	120	120,126	0,10	4,583	4,573	0,23	549,308	0,13
75	825	120	120,425	0,35	6,875	6,829	0,67	822,348	0,32
100	1100	120	120,225	0,18	9,167	9,129	0,41	1097,488	0,23

We managed to make a way through the increasingly stringent standard requirements to prove the accuracy and the effectiveness of the proposed test procedure as well as the implemented PVE. Following this study, the obtained results are compared with other research works presented in the scientific literature. Therefore, we have referred to several research works [9-10-30]. We have thus, deduced that, concerning the test procedure, most of the research papers dealing with this issue do not detail the test procedure steps or inevitably call for extremely delicate or complicated approaches. The proposed procedure is based on the PV model required by the EN 50530 standard and follows a simple methodology to achieve the tests purposes.

Table ***8*** summarizes the comparison between the proposed procedure and some others procedures presented in papers [9-10-30]

Table 8. Comparison between the proposed procedure and the references [9-10-30]

	Complexity	**Accuracy**	**Parameters**	**GUI**
Proposed procedure	Simple	<1% (P, V and I)	-PVI datasheet -EN 50530 scenarios	LabVIEW + UART
[9]	Simple	Bad THD (9,11%)	-PVI datasheet -Climatic conditions	---
[10]	Complex	Low+ high ripples	Load	dSPACE controlDesk
[30]	Complex	High	-PVI datasheet -Climatic conditions	LabVIEW

Focusing on this comparison, it can be noted that the proposed procedure offers several advantages compared to the references previously presented in Table 7. Among the most interesting advantages, we can cite the simplicity of the program implementation and the handling but also its accuracy to fulfill the requirements given by the studied standard.

Concerning the PVE model implementation mode, a tradeoff between the two typical operating modes; the "direct implementation" mode and the "Look-up implementation" mode, has been reported in scientific literature. It results in the fact that the first one allows to reproduce the PV generator behavior with a high accuracy, insomuch as an adequate number of points (current-voltage) are specified. In other words, this approach requires several parameters such as those extracted from the PVI datasheet or data obtained experimentally or the I-V points will be computed only for certain operating conditions (STC). The second mode allows to emulate the PV generator with the minimum available data, but at the expense of the accuracy with a high precision. But that drawback can be remedied by the increasing of the sample number in the Look-up table to improve the accuracy of this method. Therefore, for our test platform, we selected the use of two Look-up tables. The first one is composed of 1501 elements and the second of 3001 elements. Resulting from this choice, the adopted approach has been compared to the direct implementation method in [15]. The comparison results indicate that the error between the two implementation methodologies does not exceed 1% for different randomized conditions. It is also ascertained for the experimental results introduced in the present paper, that the PVE, based on the Look-up table approach, is able to meet the standard requirements by respecting the permitted margin of error. A comparative analysis, carried out between he direct referencing mode, the Look-up table mode and a third mode based on the linear segmentation of the I-V curve, is reported in Table 9.

Table 9. Comparison between three PV model implementation modes

	Accuracy	**Computing time**	**Memory resources**
Direct referencing mode [11]	Very highly accurate	High	Low
Look-up table mode [38-39]	Highly accurate	Low	High
Linear segmentation mode	Inaccurate	Low	Low

[40]			

5. Conclusion

In this paper, an innovative and comprehensive PVE test procedure has been introduced in order to accurately fulfill the EN 50530 test requirements for carrying out PVI Static MPPT efficiency tests. Thus, the proposed procedure steps have been explained allowing the efficient generation of the required I-V characteristics from the PVE. Indeed, the PVE control parameters are accurately determined using data provided in the PVI datasheet and basing on the EN 50530 standard requirements. A software implemented under LabVIEW environment allows one to automatically compute the required test and control parameters, to communicate them to a STM32F4 target to accurately control the PVE for a given test scenario, and to display the emulated I-V and P-V characteristics. Simulation and experimental tests have been performed and convincing results have been obtained to highlight the high accuracy of the generated PVE curves and MPP powers for all the described test scenarios. They were accomplished for the case study of a real-world 1100 W PVI. This work allows a closer step towards approaching the EN 50530 MPPT efficiency test's goals.

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