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Metrological Analysis of Sunflower Prototype

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Abstract

It is well known that the solar tracking systems can increase the efficiency of the photovoltaic (PV)
panel by about 30 percent. However, these systems require precise control of their components,
mainly of the equipment's used for the measurement of energy. In this paper, a metrology analysis
is conducted, through of the results obtained by Sunflower prototype. The Sunflower is a solar
tracking system developed by H. J. Loschi. A tracking system through a microcontrolled timing
logic, sending commands to a linear actuator that moves the system. The deductions, based on in
research trials, confirms that the Sunflower prototype is more efficient in relation to fixed PV pa-
nels, it is possible to observe the difference in the efficiency of 31%, with a variation of ±0.8%
(that depends the solar irradiation). The main purpose of this paper is to attest to the quality of
the measurements carried out during the performance tests of the Sunflower prototype, eva-
luating the uncertainty of measurements collected through the measurements equipment, and,
introducing methods to minimize uncertainties of measurement equipment in the PV systems.

Keywords

1. Introduction

In the history of metrology, ideas concerning problems of current importance, as well as methods of their solu-
tion, have qualitatively changed more than once. Such changes are caused by new requirements for industry and
society at each stage of development. These changes were taken into account in the revision of metrological leg-
islative acts and regulations [1].

Systematic effects are the most critical issue in measurement, especially in the metrological field, since their effect on the measured values and on the resulting total uncertainty are often dominant. In this respect, and considered the use of PV systems for electric power generation, it is necessary metrological suitability of the equipment used in the tests [2].

The main purpose of this paper is to attest to the quality of the measurements carried out during the performance tests of the Sunflower prototype, evaluating the uncertainty of measurements collected through the measurements equipment, such as DDM (digital multi meter) [3] [4].

The assessment begins with a brief introduction to the concept of basic greatness and influence. The third chapter introduces the boundary conditions during the period of measurements, detailed description of the measurements performed with the Sunflower prototype. The fourth chapter introduces all the components and assessment of uncertainty in measurement of electrical current and voltage, and, in the fifth chapter introduces the assessment of uncertainty in measurement of electrical power. Finally in the sixth chapter an analysis of conclusion is introduced, highlighting the applicability of method used.

2. Basic Greatness and Influences

In the PV panels, the electricity transduction occurs through the photon effect and greatest power converted, expressed in watts (W). It is known that electric power can be expressed in various ways, but most commonly is treated [5].

$$p(t) = UI\cos(\phi) \tag{1}$$

where the voltage (U) is expressed in volts (V), current (I) in ampere (A) and the angle ϕ is the electric discrepancy between voltage and current. When it is to resistive impedance, the reactances are despicable and the angle ϕ is approximately zero and Equation (1) results in [5].

$$p(t) = UI \tag{2}$$

In this way, the voltage and electric current are the values of influence on measurement and metrological evaluation of power [5] [6]. It is essential to determine the correlation between the three variables $(p(t), U, I)$, because the measurements of voltage and electrical current, were performed directly with DMM. The power was not obtained from direct measurements, was obtained, indirectly, by use of Equation (2), full details of the locations and conditions of the tests performed in sunflower prototype are introduced in the paper [3] [4].

3. Boundary Conditions during the Period of Measurements Carried out

The measurements carried out on the Sunflower prototype, voltage and electrical current, were performed in the tracking (t) and static (s) mode, will be adopted the following notation conventions, as follows: voltage tracking mode (u_{tV}), voltage static mode (u_{sV}), electric current tracking mode (u_{tI}), electric current static mode (u_{sI}). **Figure 1** and **Figure 2**, demonstrate the Sunflower prototype and PV panels, in the field test [3] [4].

The measurements of voltage and electric current were performed from 06:00 am to 06:00 pm at intervals of 10 and 10 minutes, during 5 days. **Figure 3** introduce to the graph of voltage measurement, for both, tracking and static mode, during 12 hours in 5 days [3] [4].

Figure 4, introduce to the graph of electric current measurement, for both, tracking and static mode, from 06:00 am to 06:00 pm at intervals of 10 and 10 minutes, during 12 hours in 5 days [3] [4].

The measurements of voltage and electric current were practically constant, with low oscillation, over the period from 7:10 am to 04:00 pm, other data (outliers) were discarded at the discretion of standardization, expressed by Equation (3) [7]-[9].

$$\text{Value}_{\text{STANDARD}} = \frac{\text{Value}_{\text{MEASURED}} - \mu}{\sigma} \tag{3}$$

where μ is the average value of the measurements and σ is the standard deviation of measurements. In this way, the values considered "outliers" resulted in the $\text{Value}_{\text{STANDARD}}$, it may be presented as zero or negative [7]-[9].

Figure 1. Sunflower prototype [3] [4].
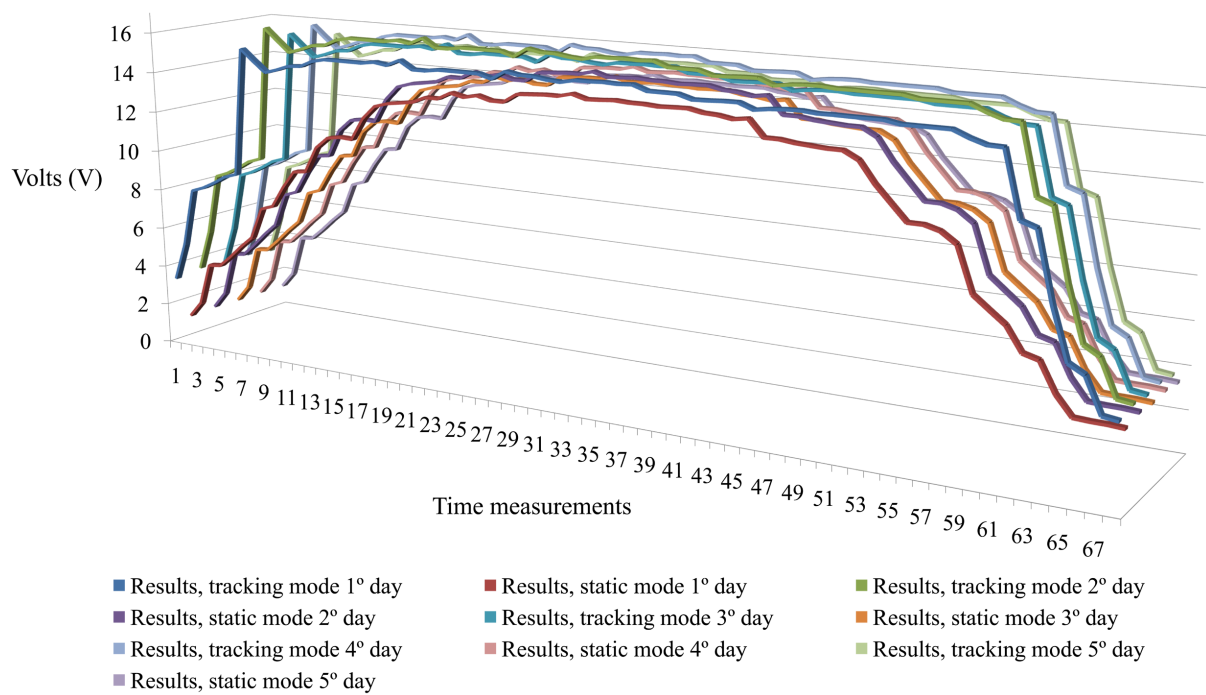

Figure 2. PV panels [3] [4].

Figure 3. Measurements of voltage in the tracking mode $\left(u_{tV} \right)$ and static mode $\left(u_{sV} \right)$ [3] [4].
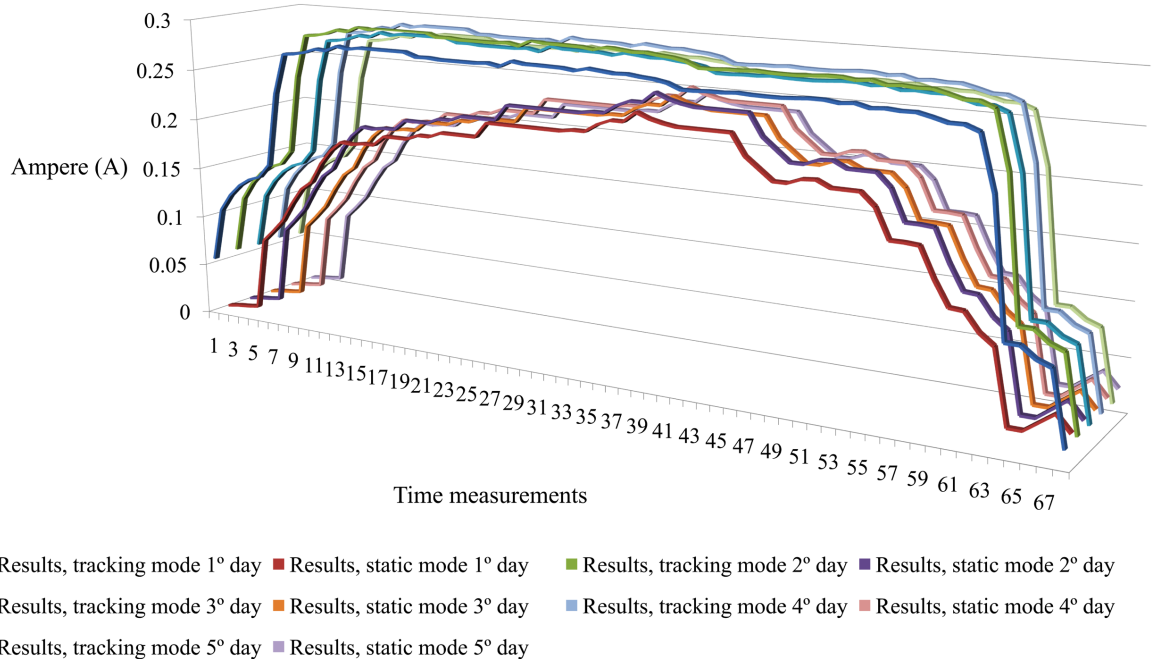
Figure 4. Measurements of electric current in the tracking mode $\left(u_{tI}\right)$ and static mode $\left(u_{sI}\right)$ [3] [4].

4. Components and Assessment of Uncertainty in the Electrical Current and Voltage

The expression of measurement uncertainty of a quantity takes into account, several components of uncertainty, which are classified, such as, "A" and "B". Basically, the difference is in the evaluation of statistical reasoning of components of uncertainty [1] [2]. As mentioned, both the voltage and electric current was measured directly through DMMs, soon, the values can be expressed by Equations (4a) and (4b) [9] [10].

$$V = \overline{V} \pm U_V \tag{4a}$$

$$I = \overline{I} \pm U_V \tag{4b}$$

In order to facilitate theoretical exposure, considers the generic notation, express by Equation (5) [7]-[9].

$$a = \overline{a} \pm U_a \tag{5}$$

where $a = V$, I. The value $\overline{a}$, expresses the arithmetic average of greatness V or I, which can be express by Equation (6) [7]-[9].

$$\overline{a} = \frac{\sum_{i=1}^{n} a_i}{n} \tag{6}$$

where a_i is the set of n measured values using a DMM. The portion U_a from Equation (5), represents the expanded uncertainty and can be express by Equation (7) [7]-[9].

$$U_a = k_a \cdot u_{ac} \tag{7}$$

where k_a refers to the coverage factor obtained from [10], to a level of confidence of 95.45% and u_{ac} refers to the combined uncertainty, calculated by quadratic combination of all measurement uncertainty components. Equation (8) illustrates the portions of component u_{ac} [7]-[9].

$$u_{ac}^2 = \sum_{j=1}^{k} \left(CS_j \cdot u_{aj}\right)^2 \tag{8}$$

The factor CS_j refers to the sensitivity coefficients of each portion of the combined uncertainty with respect to the measured. When this value is unknown, considers the worst case, which is unitary. The u_{aj} represents

the "j" portions of uncertainty components, which are express by Equation (9) [7]-[9].

$$u^2_{\alpha_c} = u^2_{\alpha_{m,\text{DMM}}} + u^2_{\alpha_{sp,\text{DMM}}} + u^2_{\alpha_{r,\text{DMM}}} + u^2_{\alpha_{f,\text{PV}}} + u^2_{\alpha_{r,\text{PV}}} \tag{9}$$

where:

➢ $u_{\alpha_{m,\text{DMM}}}$, component type "A", related to measurements carried out;

➢ $u_{\alpha_{sp,\text{DMM}}}$, component type "B", related to the percentage of the output as read on the DMM and the offset from the DMM, in accordance with the manufacturer's specifications;

➢ $u_{\alpha_{r,\text{DMM}}}$, component type "B", related to the resolution of the DMM;

➢ $u_{\alpha_{f,\text{PV}}}$, component type "B", related the manufacturer specification of the PV cell;

➢ $u_{\alpha_{r,\text{PV}}}$, component type "B", related to the resolution of the PV cell.

The component $u_{\alpha_{m,\text{DMM}}}$ is express by Equation (10).

$$u_{\alpha_{m,\text{DMM}}} = \frac{\sigma}{\sqrt{n}} \tag{10}$$

The components $u_{\alpha_{sp,\text{DMM}}}$ and $u_{\alpha_{f,\text{PV}}}$ are obtained by specifications contained, respectively, in the manuals of the DMM and manufacturers of PV cells, whose distributions are rectangular [11]. The components $u_{\alpha_{r,\text{DMM}}}$ and $u_{\alpha_{r,\text{PV}}}$ are obtained, respectively, of the resolutions of the DMM and PV cells, whose distributions also are rectangular. **Table 1**, contains the values of each component, both for voltage and electrical current and both the operating modes, tracking and static [12] [13].

Degrees of Freedom and Coverage Factor

Once calculated the components of uncertainty and the combined uncertainty of each of the variables, both for tracking and static mode, the next step is to calculate the effective degrees of liberty $\left(v_{\text{eff}}\right)$, by Equation (11) [12].

$$v_{\text{eff}_a} = \frac{u^4_{ac}}{\sum_{j=1}^{k}\left(\dfrac{u^4_{aj}}{v_j}\right)} \tag{11}$$

In this present value, analysis v_{eff} will depend, primarily, of the component $u_{am,\text{DMM}}$ in all 4 scenarios analysed (VTracking, Itracking, Vstatic, Istatic). Therefore, **Table 2**, presented the values obtained for $\bar{a}_j$, u_{ac}, v_{eff_a}, k_a, U_a and, finally, the expression of measurement uncertainty (α) for the situations mentioned.

5. Assessment of the Measurement Uncertainty of Electric Power

The algebraic expression that relates voltage and current is express by Equation (2) and the electric power values were determined by calculations involving the quantities V and I. In this scenario, for the determination of electric power values related to values of correlated quantities, it is necessary the use of covariance resource for determining the uncertainty of measurement of electrical power. The following Equation (12) expresses the calculation for correlated quantities [7] [13].

$$u^2_{P_C} = \left[\frac{\partial}{\partial V}(P)\right]^2 \cdot u^2_V + \left[\frac{\partial}{\partial I}(P)\right]^2 \cdot u^2_I + 2\cdot\left[\frac{\partial}{\partial V}(P)\right]\cdot\left[\frac{\partial}{\partial I}(P)\right]\cdot u_V u_I \cdot r(V,I) \tag{12}$$

Measurement uncertainties are estimated for both Ptracking (correlates Vtracking and Itracking) and Pstatic (correlates Vstatic and Istatic). It is considered the experimental average and the experimental standard deviation to express the uncertainties of electrical power from the PV panel. **Table 3** presented the average values obtained for power electrical $\overline{tP}$, $\overline{sP}$, the correlation coefficients CC_{TP}, CC_{SP}, the combined uncertainties u_{P_c}, the factors included k_p and their uncertainties u_{tP_c}, u_{sP_c}.

Table 1. Record of voltage and electrical current measurements.

Voltage measurements (tracking)				Current measurements (tracking)			
Component	Value	Distribution	Type	Component	Value	Distribution	Type
$u_{tV_m,\text{DMM}}$	0.0426 V	Normal	A	$u_{tI_m,\text{DMM}}$	0.0011 A	Normal	A
$u_{tV_{sp},\text{DMM}}$	0.0622 V	Rectangular	B	$u_{tI_{sp},\text{DMM}}$	0.0148 A	Rectangular	B
$u_{tV_r,\text{DMM}}$	0.0029 V	Rectangular	B	$u_{tI_r,\text{DMM}}$	0.0029 A	Rectangular	B
$u_{tV_f,\text{PV}}$	0.3584 V	Rectangular	B	$u_{tI_f,\text{PV}}$	0.0058 A	Rectangular	B
$u_{tV_r,\text{PV}}$	0.0029 V	Rectangular	B	$u_{tI_r,\text{PV}}$	0.0029 A	Rectangular	B
u_{tV_c}	0.3663 V			u_{tI_c}	0.0163 A		
Voltage measurements (static)				Current measurements (static)			
Component	Value	Distribution	Type	Component	Value	Distribution	Type
$u_{sV_m,\text{DMM}}$	0.1942 V	Normal	A	$u_{sI_m,\text{DMM}}$	0.0033 A	Normal	A
$u_{sV_{sp},\text{DMM}}$	0.0622 V	Rectangular	B	$u_{sI_{sp},\text{DMM}}$	0.0148 A	Rectangular	B
$u_{sV_r,\text{DMM}}$	0.0029 V	Rectangular	B	$u_{sI_r,\text{DMM}}$	0.0029 A	Rectangular	B
$u_{sV_f,\text{PV}}$	0.3584 V	Rectangular	B	$u_{sI_f,\text{PV}}$	0.0058 A	Rectangular	B
$u_{sV_r,\text{PV}}$	0.0029 V	Rectangular	B	$u_{sI_r,\text{PV}}$	0.0029 A	Rectangular	B
u_{sV_c}	0.4124 V			u_{sI_c}	0.0166 A		

Table 2. Expression of measurement uncertainty of voltage and current.

Greatness	$\bar{\alpha}$	u_{ac}	v_{eff_a}	k_α	U_α	$\alpha = \bar{\alpha} \pm k_\alpha U_\alpha$
tV	15.4968 V	0.3663 V	>100	2	0.7326 V	(15.50 ± 0.73) V
sV	13.7307 V	0.4124 V	>100	2	0.8455 V	(13.73 ± 0.82) V
tI	0.2830 A	0.0163 A	>100	2	0.0326 A	(0.28 ± 0.03) A
sI	0.2146 A	0.0166 A	>100	2	0.0332 A	(0.21 ± 0.03) A

Table 3. Expression of measurement uncertainty of electric power.

Greatness	$\bar{P}$	cc_p	u_{P_c}	v_{eff_p}	k_p	$P = \bar{P} \pm k_p U_P$
tP	4.3895 W	0.418	0.0145 W	>100	2	(4.38 ± 0.03) W
sP	2.9855 W	0.877	0.0526 W	>100	2	(2.99 ± 0.11) W

6. Conclusions

The metrological analysis of the Sunflower Prototype, method presented in this paper concerns the specific data of the measurements carried out during the performance tests. The methodology, presented in the paper, for testing and describing the metrological properties of the measurements collected though the measurements equipment's, and introducing methods to minimize uncertainties of measurement equipment in the PV systems. The determination of the distribution for an output quantity, using the propagation of distributions, through a DDM, proved to be appropriate. The concepts of probability theory provide a unique, self-consistent method for quantitative reasoning given incomplete information. In the case of measurement data evaluation, they permit the rigorous treatment of non-linear measurement models that, for particular reasons, cannot validly be linearized.

It is possible to decrease the measurement uncertainty through the following factors:
- Decrease the time interval considered as representative measurements carried out, taking into account only the 4 hours of greater solar intensity, which would imply in the range of measured from 30 to 35 values. This reduced of the sample space would allow them to be used the methods of Dixon, Cochran and Grubbs to de-

termining the outliers;

- Using DMMs with 5½ or 6½ digit, to decrease the component type A of measurement uncertainty and even the component type B, concerning the resolution of the instrument.

The powers (Ptracking and Pstatic) were not measures, were obtained through calculations performed with the measures of V and I, which makes the measurement uncertainty of power be calculated through correlation of variables. It is possible to decrease the uncertainty of measurement of power, replacing the indirect for direct methodology, *i.e.* made using energy meters or wattímetros.

Acknowledgements

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