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Methodology to Define an Overall Efficiency of Photovoltaic Inverters Considering Static and Dynamic Tests

Henrique Horst Figueira[1], **Fernando S. Scherer**[2], **Ricardo J. F. Bortolini**[2], **Lucas Vizzotto Bellinaso**[2], **Leandro Michels**[2]

[1]SEG Automotive Germany GmbH, Engineering hardware department, Stuttgart - BW, Germany.
[2]Federal University of Santa Maria, Power Eletronics and Control Group, Santa Maria, RS, Brazil.

e-mail: hhfigueira@gmail.com; fernando.scherer@acad.ufsm.br; rjochann@gmail.com; lucas@gepoc.ufsm.br; michels@gepoc.ufsm.br

ABSTRACT Efficiency indices for inverters have been developed with the increasing adoption of photovoltaic (PV) systems. The European and Californian efficiencies are widely recognized, focusing on static inverter operation. Standards such as EN50530 and IEC 62891 introduced dynamic efficiency tests considering irradiance variations, but without a methodology to weigh the efficiencies within a single index. To address this gap, our study proposes a methodology to define an overall efficiency considering both static and dynamic inverter operation. Irradiance data with sub-minute sampling is classified into irradiance and irradiance derivative ranges. Then, weights for static and dynamic efficiency tests are obtained, and less significant ones are discarded. The results were applied to three PV inverters tested in the laboratory. By eliminating the less significant tests, the number of dynamic tests was reduced from 30 to 10. In two of the inverters, the inclusion of dynamic tests resulted in a 2% reduction in overall efficiency compared to the static. An overall efficiency index is relevant for better comparing different PV inverters, especially when considering dynamic behaviors. This index may be significant for the PV market, governmental energy efficiency programs, and inverter manufacturers, providing guidelines to enhance the efficiency of their products.

KEYWORDS Photovoltaic System Efficiency, Natural Solar Dynamics, Renewable Energies, Global Efficiency, Static Efficiency, Dynamic Efficiency.

I. INTRODUCTION

With the increasing adoption of grid-connected photovoltaic (PV) systems, indices have been created to evaluate and compare the efficiency of inverters. The efficiency of PV inverters can be divided into two stages: conversion efficiency, which is the average power on the AC side divided by the average power on the DC side; and MPPT efficiency, which is the average DC side power divided by the maximum average power that the PV array can provide [1] [2] [3]. The conversion efficiency depends on multiple factors, mainly the current operating power, dependent on solar irradiance, the voltage of the photovoltaic array, and temperature. Meanwhile, MPPT efficiency depends on the behavior of the MPPT algorithm during static and dynamic changes of solar irradiance [3]. The static MPPT efficiency focuses on the inverter's performance under constant solar irradiation and temperature conditions [3]. On the other hand, the dynamic MPPT efficiency is an indicator of the inverter's ability to quickly adjust to changes in solar irradiation [4].

Other important indices are the weighted efficiencies, which offer a more realistic indication of how inverters can perform throughout the day considering the inverter's performance across its entire capacity range. They were created as a way to combine simplicity and accuracy in measuring overall efficiency, without the need for an annual system simulation using point-to-point inverter efficiency. This facilitates the comparison between different models and brands of inverters, allowing professionals and consumers to make decisions for equipment selection, and also encouraging the advancement of inverter technology. The most commonly used weighted efficiencies are Californian [5] [6] and European [2], obtained during steady-state operation of the inverter at various operating powers and at three voltages on the DC side (minimum, maximum, and nominal). The IEC 62891 [7] and EN50530 [2] technical standards defined the processes for calculating weighted efficiencies from experimental results of inverters. These standards also included the calculation of dynamic efficiencies, which are the average efficiencies calculated during power variations of the inverter due to natural variations in irradiance due to cloud passage and change in solar position.

With the inclusion of dynamic efficiencies in the standards, a new challenge arose: the complexity in interpreting and comparing the multiple resulting numbers, without a clear definition of how to weight them. This compromised the original goal of weighted efficiencies, which was to provide a single measure of the overall efficiency of inverters. In order to compare the efficiency of different models and brands of inverters, it is important to have a single index of overall efficiency, weighting both static and dynamic efficiencies.

This paper aims to overcome the ambiguity resulting from multiple indices by proposing a methodology for weighting static efficiencies (Californian or European) with dynamic MPPT efficiencies and obtaining a single overall efficiency index. The weightings for dynamic efficiency are obtained from the analysis of high-frequency irradiance data. The results of dynamic efficiency tests required in the IEC 62891 and EN50530 standards are weighted after analyzing the frequency distribution of the irradiance derivative. Through data analysis, it is possible to identify the tests that most impact overall efficiency.

The proposed methodology for defining the overall efficiency of PV inverters, considering both static and dynamic analysis, is important for enabling direct comparisons among various inverter models, thus becoming a reference for the PV market. Moreover, through the proposed methodology, it was possible to reduce the total number of tests by excluding those identified as less significant for calculating overall efficiency, thereby saving time and laboratory resources.

The main contributions of this paper are:

1) **Development of a Methodology for Weighting Static and Dynamic Efficiencies:** elaboration of an approach for the evaluation of PV inverters, incorporating both static and dynamic efficiencies. This methodology takes into account the natural solar dynamics, providing a more comprehensive and realistic analysis of inverter performance.
2) **Definition of a Single Overall Efficiency Index:** establishment of a unified overall efficiency parameter for PV inverters. This index, which weights both static and dynamic efficiency, offers a tool for the PV market compare different inverter models. This index can be applied in governmental energy efficiency programs, such as the Brazilian Labeling Program (Programa Brasileiro de Etiquetagem - PBE) of the National Institute of Metrology, Standardization, and Industrial Quality (INMETRO) [8], to help consumers compare different inverter brands and models. Static efficiency tests are already mandatory in this program, but the inclusion of dynamic tests would provide a more meaningful index.
3) **Reduction of Dynamic Efficiency Tests:** determination of the most relevant dynamic efficiency tests on the overall efficiency of PV inverters. This enables the optimization of the testing process, reducing the number of necessary tests and, consequently, saving time and laboratory resources.

II. PV INVERTER EFFICIENCY STANDARDS

This section details the test criteria established by the IEC 62891:2020 standards and the California CEC (Sandia Test Protocol) for the evaluation of PV inverters. The tests cover functionality and conversion efficiency of the equipment. Figure 1 illustrates the layout of the test bench according to the standards, including the DC input, the AC output, the Equipment Under Test (EUT) and the measurement instruments (voltage, current, power, energy).

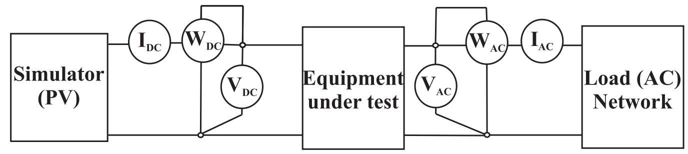

FIGURE 1. Schematic of the test bench recommended by IEC 62891:2020.

A. Static efficiency

The International Electrotechnical Commission (IEC) established the IEC 61683 standard in 1999, marking the beginning of guidelines for evaluating the energy efficiency of PV inverters. The most updated version of this standard is IEC 62891:2020. The main requirements set by the standard are as follows:

Environmental Requirements: As specified by the manufacturers, the measurement devices should operate under defined environmental conditions. In IEC 61683, the EUT is evaluated in a controlled ambient temperature of 25°C ± 5°C, after the inverter reaches the steady state temperature at the desired power. The CEC standard additionally includes evaluations at an ambient temperature of 40°C.

Static Efficiency Test Variations: The tests cover up to eight power levels (5%, 10%, 20%, 25%, 30%, 50%, 75%, and 100%) and 3 different DC input voltages: the minimum voltage specified by the manufacturer, the nominal input voltage, and an input voltage equivalent to 90% of the maximum voltage. In total, 24 tests are conducted, with all measurements performed after the inverter reaches steady state.

Other Tests: The standard also includes other tests that are not considered here for defining overall efficiency:

- No-Load Loss Test (IEC 61683 and CEC): measures the power consumed by the EUT in no-load operation on the AC side.
- Standby Loss Tests (IEC 61683 and CEC): assesses the power consumed on the AC side when there is no power input on the DC side.
- Maximum Continuous Output Power (CEC): determines the maximum power the EUT can continuously provide for 180 minutes at an ambient temperature of 40°C.

Efficiency of a PV inverter in a given test condition can be calculated by dividing the average output power by the average input power. Alternatively, can be calculated by the output energy divided by the input energy within a defined period:

$$\eta_E = \frac{P_o}{P_i} \cdot 100\% = \frac{W_o}{W_i} \cdot 100\%. \quad (1)$$

The weighted efficiency for multiple power operation points can be calculated by:

$$\eta_{\text{weighted}} = F_5\eta_5 + F_{10}\eta_{10} + F_{20}\eta_{20} + F_{25}\eta_{25} + F_{30}\eta_{30} + F_{50}\eta_{50} + F_{75}\eta_{75} + F_{100}\eta_{100}, \quad (2)$$

Where F_x is the weight that reflect the proportion of energy produced around $x\%$ of nominal power, where the inverter efficiency is η_x. The energy produced at each power range is obtained through simulation, considering irradiance history of the installation site [7] and the PV array with the same inverter power. The Californian (CEC) and European (Euro) efficiency coefficients are shown in Table 1.

B. Dynamic Efficiency

In the dynamic efficiency tests outlined in IEC 62891, the irradiance emulated in PV sources is changed in the form of ramps, with slopes ranging from 0.5 W/m²/s to 100 W/m²/s. These ramps are characterized by their ramp-up and ramp-down times, as well as dwelling times for both the upper and lower values. The tests can last from 10 to 38 minutes. Irradiance ramps simulate real variations in irradiance conditions a PV inverter may face [9]. The dynamic MPPT efficiencies are calculated as shown in Equation 1 for the entire duration of each test, considering W_i the maximum energy the PV generator could deliver for the simulated irradiance.

III. METHODOLOGY

A. Irradiance Data Acquisition

Irradiance data needed to calculate the weighted efficiencies are typically obtained through measurements with pyranometers over the course of a typical year. To obtain these data accurately, it is important to define two parameters: the bandwidth (or time constant) of the pyranometer and the sampling period.

Pyranometers can be classified into two main types: thermoelectric and photoelectric. Thermoelectric pyranometers use a black surface to absorb radiation and convert it into an electrical signal proportional to the heat, with a typical bandwidth of 0.2 Hz [10]. On the other hand, photoelectric pyranometers use photodiodes to absorb radiation, offering a faster response and an absorption spectrum similar to photovoltaic modules [11] [12]. These photoelectric pyranometers have a typical bandwidth greater than 1 Hz for calibrated photovoltaic cells [13], and photodiode pyranometers can achieve a bandwidth of 1 MHz [14].

TABLE 1. Weights of CEC and Euro Efficiencies.

	F_5	F_{10}	F_{20}	F_{25}	F_{30}	F_{50}	F_{75}	F_{100}
CEC	0	0.04	0.05	0	0.12	0.21	0.53	0.05
Euro	0.03	0.06	0.13	0	0.1	0.48	0	0.2

1) Pyranometer bandwidth requirement

Fast dynamics of the pyranometer is important to measure irradiance variations with low error. Considering a pyranometer with a first-order transfer function between the incident irradiance G_{inc} and the measured irradiance G_m:

$$G_{pyr}(s) = \frac{G_m(s)}{G_{inc}(s)} = \frac{1}{s\tau_{pyr} + 1}, \quad (3)$$

where τ_{pyr} is the time constant of the pyranometer, which is the inverse of its bandwidth in rad/s.

The static error e_G between G_{inc} and the measured irradiance G_m for a ramp variation of the irradiance can be calculated using the final value theorem:

$$\lim_{t\to\infty} e_G(t) = \lim_{s\to 0} s\frac{r}{s^2}\left(1 - \frac{1}{s\tau_{pyr} + 1}\right) = r\tau_{pyr}, \quad (4)$$

where r is the ramp derivative, in W/m²/s.

The maximum considered irradiance derivative is $r = 100$ W/m²/s. Considering a maximum error of 10 W/m², which is 1% of the maximum of 1000 W/m², the maximum time constant of the pyranometer would be 0.1 s, which is a bandwidth of 10 rad/s. This justifies the need of using photoelectric pyranometers instead of thermoelectric pyranometers, which have slower dynamics.

2) Irradiance sampling period

The definition of the sampling period depends on the characterization of the triangular waveform used in the tests. The minimum period of the triangular irradiance variation considered for the dynamic tests is 60 s, so the fundamental frequency would be 1/60 Hz. Triangular periodic functions have odd harmonics different from zero. In order to capture irradiance variations up to the 5th harmonic of this triangular waveform, the minimum irradiance measurement frequency would be two times 5/60 Hz, according to the Nyquist-Shannon Theorem. So, the minimum measurement period would be 6 s. A smaller sampling period would improve the measurement. In this paper, the sampling period considered is 1 s.

B. Calculation of weighting factors

The overall efficiency of the proposed method is calculated by multiplying the efficiencies obtained at various operating points by weighting factors:

$$\eta_{tot} = \sum_g \sum_v F_{g,v}\eta_{g,v}, \quad (5)$$

where: g represents the irradiance range, with the objective of identifying in which irradiance range there is a higher probability of large irradiance steps occurring. For this purpose, six ranges have been defined, where irradiance g will be separated, equivalent to those used by the CEC [15]. The irradiance ranges are defined as follows:

- **Range A:** 0 W/m² to 150 W/m²;
- **Range B:** 150 W/m² to 250 W/m²;
- **Range C:** 250 W/m² to 400 W/m²;
- **Range D:** 400 W/m² to 625 W/m²;
- **Range E:** 625 W/m² to 875 W/m²;
- **Range F:** greater than 875 W/m².

v is the irradiance variation range, separated into the following 6 ranges:

- **Range I (static level)**: from 0 W/m²/s to 5 W/m²/s;
- **Range II**: 5 W/m²/s to 15 W/m²/s;
- **Range III**: 15 W/m²/s to 25 W/m²/s;
- **Range IV**: 25 W/m²/s to 35 W/m²/s;
- **Range V**: 35 W/m²/s to 65 W/m²/s;
- **Range VI**: greater than 65 W/m²/s.

$\eta_{g,v}$ is the average efficiency (MPPT and conversion) of the inverter operating in irradiance range g and irradiance variation range v.

$F_{g,v}$ is the weighting factor related to irradiance range g and irradiance variation range v. The sum of the weighting factors is 1:

$$\sum_g \sum_v F_{g,v} = 1. \tag{6}$$

The overall efficiency can be divided into static and dynamic efficiency, considering only the range of irradiance variation I for static efficiency, and ranges II to VI for dynamic efficiency. The resulting equations are:

$$\eta_{stat} = \frac{\sum_g F_{g,\mathrm{I}} \eta_{g,\mathrm{I}}}{\sum_g F_{g,\mathrm{I}}}. \tag{7}$$

$$\eta_{dyn} = \left. \frac{\sum_g \sum_v F_{g,v} \eta_{g,v}}{\sum_g \sum_v F_{g,v}} \right|_{v \in (\mathrm{II}, \cdots, \mathrm{VI})}. \tag{8}$$

Equation 7 considers the percentage of low irradiance derivative in the irradiance range, while equation 2 is more suitable for calculating static efficiency when dynamics are disregarded.

1) Irradiance correction for tilt and module temperature

The power output of PV modules depends on the angle of incidence of the irradiance. Maximum power is achieved when the irradiance is perpendicular to the module surface. Irradiance data from the solarimetric station can be obtained directly on the plane of the PV modules or only on the horizontal plane (Global Horizontal Irradiance - GHI). When obtained on the horizontal plane, it is necessary to convert the data to the irradiance incident on the inclined plane, considering a PV system with fixed orientation [16].

However, just converting the irradiance to the inclined plane is not enough to estimate the power output of the PV array. The power of silicon modules reduce as the temperature increases. The temperature of the module T_{pv} can be estimated with the following equation, which depends on the incident irradiance on the inclined plane G_{inc} and the ambient temperature T_{amb} [16]:

$$T_{pv} = 0.943 \cdot T_{amb} + 0.028 \cdot G_{inc} + 4.3. \tag{9}$$

From T_{pv}, the equivalent irradiance G_{corr} can be estimated as if the module were always at 25°C [17]:

$$G_{corr} = G_{inc} \cdot (1 - K_{pv} \cdot (T_{pv} - 25)), \tag{10}$$

where K_{pv} is the power reduction constant of the PV module, in p.u./°C.

This temperature-corrected irradiance, although not real, becomes proportional to the power generated by the photovoltaic array. This corrected irradiance is used for calculating the weights of the overall efficiency of photovoltaic inverters. This irradiance correction model can be applied to any PV module technology, where the solar energy is almost entirely absorbed by the module and predominantly converted into thermal energy.

2) Weighting factors for irradiance ranges

The weighting factors $F_{g,v}$ are calculated for 6 irradiance ranges and 6 irradiance variation ranges, where $g \in$ (A, B, C, D, E, F) and $v \in$ (I, II, III, IV, V, VI). First, the weighting factor k_g for each irradiance range g is obtained. Two approaches can be considered:

1) Considering usual efficiencies such as CEC and Euro: using the factors of Table 1 for the irradiance ranges. This approach is the one used in the results of Section IV, considering the CEC efficiency.
2) Considering measurement data: in this case, the weights can be calculated using the corrected irradiance:

$$k_g = \frac{\sum G_{corr,g}}{\sum G_{corr}}, \tag{11}$$

where:

$\sum G_{corr}$ is the sum of the corrected irradiance points over the entire measurement year;

$\sum G_{corr,g}$ is the sum of the corrected irradiance points over the measurement year that falls within the irradiance range g;

$\sum_g k_g = 1$, for $g \in$ (A, B, C, D, E, F).

3) Weighting factors within each irradiance range

For each irradiance range g, the factor $k_{g,v}$ is calculated:

$$k_{g,v} = \frac{\sum G_{corr,g,v}}{\sum G_{corr,g}}, \tag{12}$$

where:

$\sum G_{corr,g,v}$ is the sum of the corrected irradiance points within range g over the measurement year that change within

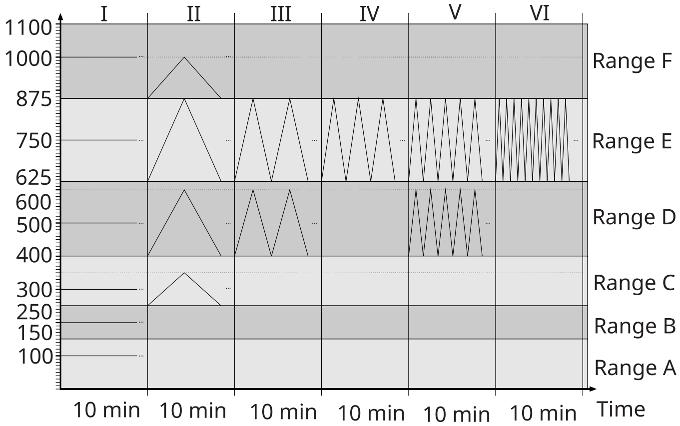

FIGURE 2. Example test map.

the irradiance variation range v, taking into account adjacent sample points;

$\sum_v k_{g,v} = 1$, for a given g and $v \in$ (I, II, III, IV, V, VI). Then, the weighting factor $F_{g,v}$ is calculated by:

$$F_{g,v} = k_{g,v} k_g. \tag{13}$$

Finally, it is proposed to eliminate the weighting factors $F_{g,v}$ smaller than 1%, redistributing their values to the adjacent irradiance change ranges v for the same irradiance range g. This way, the analysis process can be optimized, reducing the number of tests necessary by focusing on the most important cases.

C. Laboratory Efficiency Tests

Laboratory tests are conducted considering the inverter sized for the nominal power of the photovoltaic system, where the corrected irradiance of 1000 W/m² corresponds to the nominal power of the inverter. Up to 6 efficiency tests are performed with static power and up to 30 variable power tests according to irradiance variation ranges. The number of tests can be reduced when weighting factors are less than 1%. Figure 2 shows an example of test maps where a large portion of the tests from irradiance variation ranges III to VI are disregarded, as their weighting factor did not reach 1%.

For the tests, the Photovoltaic Array Simulator must be controlled to operate with a variable photovoltaic V-I curve, according to the different irradiance variation ranges (I to VI). Additionally, it is essential to know the maximum power of each instantaneous V-I curve to calculate the total efficiency of the photovoltaic inverter in the g and v ranges. A high-precision power/energy meter must be used for efficiency measurements, according to the IEC 62891:2020 standard.

IV. RESULTS AND DISCUSSION

The methodology was applied using an open solarimetric data from a station in Hawaii [18]. The experimental results of static and dynamic efficiency were obtained for 3 different PV inverters in the Inverter Testing Laboratory of Federal University of Santa Maria. The laboratory is accredited by the Brazilian National Institute of Metrology, Standardization and Industrial Quality (INMETRO) to carry out efficiency tests on PV inverters.

A. Irradiance Data Acquisition

This study used data from the Oahu Solar Measurement Grid solarimetric station in Oahu, Hawaii, USA (Latitude: 21.31034° N, Longitude: 158.08675° W). Irradiance measurements were carried out using the LI-200 photodiode pyranometer from LI-COR Inc., with a frequency of 1 Hz, positioned at 21.31478° N, 158.07785° W, at a height of 2.1 m above the ground and connected to a 100 Ω resistor. Irradiance measurements were carried out from March 2010 to October 2011. Ambient temperature was measured by the nearby solarimetric station using the CS215-L sensor [19]. The dataset [18] is open and provided by NREL. Figure 3 shows the Global Horizontal Irradiance (GHI) and ambient temperature measured in one day, during the period from 5 am to 8 pm.

B. Calculation of weighting factors

First, the GHI was converted into the incident irradiance on a plane with tilt equal to the Latitude (21°). Then, the points of corrected irradiance G_{corr} were calculated considering the temperature, as per equations (9) and (10). Figure 4 shows the example for one day, where the incident irradiance is corrected by the temperature.

Table 2 presents the calculated $k_{g,v}$ values within each irradiation range g. The parameter $k_{g,v}$ represents the frequency distribution of variations within a specific irradiation range. For the low irradiance ranges (g = A and B), $k_{g,v}$ is predominantly static (v = I), indicating minimal dynamic variation below 250 W/m². In contrast, for ranges C to F, the proportion of static operation falls below 90%, suggesting increased variability at higher irradiance levels. The highest irradiance variability is observed in the middle range D.

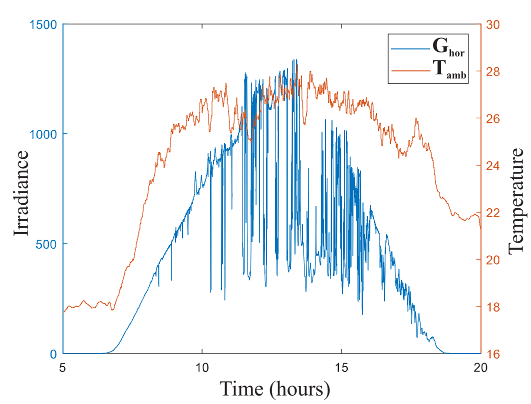

FIGURE 3. Solarimetric data: Global Horizontal Irradiance and temperature.

TABLE 2. Calculation of weighting factors $F_{g,v}$ and rounded weighting factors $F_{g,v\ (1\%)}$ considering k_g of the CEC efficiency.

Inverter	Irradiance			Irradiance variation range v (absolute W/m²/s)					
Power (%)	range g (W/m²)	k_g		I (0 - 5)	II (5 - 15)	III (15 - 25)	IV (25 - 35)	V (35 - 65)	VI (> 65)
100	F (875 - 2000)	5 %	$k_{g,v}$	83.33%	8.97%	3.49%	1.74%	1.90%	0.55%
			$F_{g,v}$	4.16%	0.44%	0.17%	0.080%	0.095%	0.027%
			$F_{g,v\ (1\%)}$	4 %	1 %	0%	0%	0%	0%
75	E (625 - 875)	53 %	$k_{g,v}$	86.47%	5.97%	2.61%	1.53%	2.12%	1.29%
			$F_{g,v}$	45.83%	3.16%	1.38%	0.81%	1.12%	0.68%
			$F_{g,v\ (1\%)}$	46 %	3 %	1 %	1 %	1 %	1 %
50	D (400 - 625)	21 %	$k_{g,v}$	78.82%	9.91%	4.12%	2.32%	3.12%	1.68%
			$F_{g,v}$	16.55%	2.082%	0.86%	0.48%	0.65%	0.35%
			$F_{g,v\ (1\%)}$	17 %	2 %	1 %	0%	1%	0%
30	C (250 - 400)	12 %	$k_{g,v}$	87.00%	7.89%	2.48%	1.16%	1.16%	0.30%
			$F_{g,v}$	10.44%	0.9471%	0.2982%	0.13%	0.13%	0.036%
			$F_{g,v\ (1\%)}$	11 %	1 %	0%	0%	0%	0%
20	B (150 - 200)	5 %	$k_{g,v}$	95.87%	3.11%	0.65%	0.2164%	0.1365%	0.0115%
			$F_{g,v}$	4.79%	0.15%	0.032%	0.01%	0.0068%	0.0006%
			$F_{g,v\ (1\%)}$	5 %	0%	0%	0%	0%	0%
10	A (0 - 150)	4 %	$k_{g,v}$	99.85%	0.136%	0.012%	0.002%	0.0008%	0.0001%
			$F_{g,v}$	3.994%	0.005%	0.0004%	0.00008%	0.000032%	0.000001%
			$F_{g,v\ (1\%)}$	4 %	0%	0%	0%	0%	0%

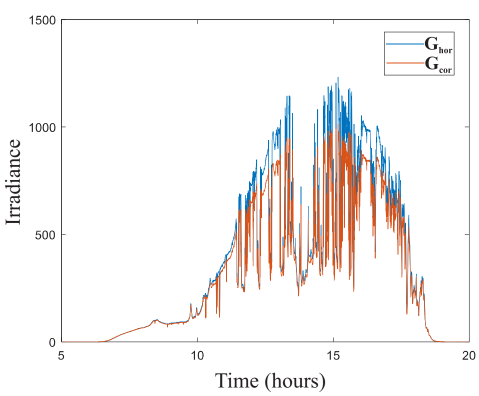

FIGURE 4. Irradiance incident on the plane vs corrected irradiance.

Following the approach 1 of Section III.B.2, the weighting factors k_g for each irradiance range $g \in$ (A, B, C, D, E, F) were considered the same of the CEC efficiency coefficients of Table 1. Then, $F_{g,v}$ is calculated using equation (13) and rounded to values greater than 1%. As a results, the static efficiency (range I) represents 87% of the overall efficiency, while the dynamic efficiency (ranges II to VI) represents 13%.

The rounded values $F_{g,v\ (1\%)}$ are used to calculate the overall efficiency as shown in equation (5). By dismissing the tests that do not influence the overall efficiency, the number of dynamic efficiency tests is reduced from 30 to 10, as shown in Figure 2. Note that the sum of $F_{g,v}$ below 1% is around 2.00%. If there were an average reduction of 10% in the dynamic efficiency at these untested points compared to the adjacent tested ones, the overall efficiency would decrease by only 0.2%. The proposed overall efficiency is an index to compare different inverters without significantly increasing the complexity of the tests. A reduction of 0.2% in the overall efficiency would not justify the inclusion of 20 additional testing points.

C. Tests results with three photovoltaic inverters

The presented methodology was applied to three PV inverters: one with 3 kW, another with 6 kW, and the third with 12 kW, designated as Inverter A, Inverter B, and Inverter C, respectively, to maintain confidentiality regarding the manufacturer/brand.

The tests were conducted using a *LabView* supervisory system and a Keysight N8957APV Photovoltaic Array Simulator. The grid was emulated using an AC Power Source. A high precision power analyzer LMG670 (ZES Zimmer GmbH) was used to measure efficiency, with 151 kS/s and a reading accuracy of 0.01% + 0.02% of the reading and upper range values, respectively. The efficiency results for Inverters A, B, and C are shown in Tables 3, 4, and 5, respectively.

Fig. 5 shows the dynamic efficiency laboratory results for Inverter A. The graphs for the other inverters are omitted here as they do not provide additional information. The lowest measured dynamic efficiency of Inverter A was 42.69% (Fig. 5(f)) and the highest was 92.47% (Fig. 5(a)). In Figures 5 (a) and (d), the output power is always proportional to the maximum PV power, indicating stability in the inverter MPPT algorithm for the irradiation variation lower than 15 W/m²/s. However, as the irradiance derivative increases, as depicted in Figures 5 (b), (c), (e), (f), (g), and (h), the output power deviates from the proportion of the maximum PV power, suggesting instability in the MPPT algorithm for irradiance derivatives exceeding 15 W/m²/s. Despite the final

TABLE 3. Measured efficiencies $\eta_{g,v}$ for inverter A (3 kW).

Range	I	II	III	IV	V	VI
F	92.36%	92.65%				
E	91.90%	92.71%	53.99%	42.69%	50.86%	70.66%
D	93.27%	92.47%	69.26%		75.63%	
C	92.30%	88.01%				
B	90.74%					
A	83.81%					

TABLE 4. Measured efficiencies $\eta_{g,v}$ for inverter B (6 kW).

Range	I	II	III	IV	V	VI
F	92.48%	92.72%				
E	93.29%	78.31%	93.55%	93.50%	93.50%	93.41%
D	93.98%	94.11%	94.07%		94.01%	
C	94.02%	94.34%				
B	92.90%					
A	89.48%					

TABLE 5. Measured efficiencies $\eta_{g,v}$ for inverter C (12 kW).

Range	I	II	III	IV	V	VI
F	95.28%	93.80%				
E	95.56%	62.52%	91.07%	90.86%	68.90%	65.22%
D	96.15%	91.73%	92.20%		78.05%	
C	96.37%	71.40%				
B	95.86%					
A	94.50%					

TABLE 6. Comparison of static, dynamic and overall efficiency of the inverters.

Efficiency	Inverter A	Inverter B	Inverter C
Static (Eq. 2)	91.88%	93.31%	95.74%
Static (Eq. 7)	91.80%	93.28%	95.73%
Dynamic	77.45%	90.17%	78.66%
Overall	89.93%	92.88%	93.51%

dynamic efficiency being below 80%, it only reduced the overall efficiency of Inverter A by 2% compared to static efficiency. The 2% deviation is frequently disregarded in PV system simulators, which commonly adopt a minimum irradiance measurement sampling period of 1 minute and do not account for the dynamic behavior of the inverter.

It can be observed in Fig. 5 the repeatability of the inverter efficiency test results is ensured by the repetition of the triangular waves, allowing for a consistent analysis of efficiency under dynamic irradiance variations. With more triangular waves, greater repeatability is achieved.

In Fig. 6, the comparison of the three inverters tested in operation for range D can be observed: inverter A of 3 kW, inverter B of 6 kW, and inverter C of 12 kW, represented respectively by (a), (b), and (c) in Fig. 6. It is noted that the first inverter experienced some moments of disconnection due to MPP variation, resulting in low dynamic efficiency values. However, the same did not occur for the other inverters of 6 kW and 12 kW. It is important to highlight that different inverters were tested, and this result may be related to the quality of the other inverters, which did not disconnect due to MPP variation.

D. Comparison of static, dynamic and overall efficiencies

Using the values of $F_{g,v\ (1\%)}$ from Table 2, the calculated static efficiency (range I), dynamic efficiency (ranges II to VI), and overall efficiencies of the three inverters are shown in Table 6.

Inverter C had similar dynamic efficiency of inverter A ($<$ 80%). On the other hand, inverter B had much better dynamic behavior, having the dynamic efficiency closer to the static efficiency. Although inverters A and C had low dynamic efficiency, this only had a 2% impact on overall efficiency. This is because the weight calculated to dynamic efficiency in the overall calculation was only 13%.

However, despite this seemingly small 2% difference, it can significantly affect the energy production of a PV system over its lifetime. This discrepancy is often disregarded during the selection of PV inverters due to the absence of a singular index like the proposed overall efficiency. Moreover, in the official government program PBE/INMETRO [8], if the efficiency value reported by the manufacturer exceeds the laboratory-measured value by more than 1%, the equipment would be disqualified. Additionally, existing PV system simulators do not incorporate the sub-minute dynamics of inverters. Therefore, this study highlights the importance of considering dynamic and static efficiency to obtain a more accurate prediction of energy production from PV systems.

V. CONCLUSION

This study proposed a methodology for obtaining a single overall efficiency index for PV inverters by weighing both static and dynamic efficiency, using high-frequency irradiance data. In the case study, the weightings resulted in 87% for static efficiency and 13% for dynamic efficiency. Experimental results were obtained with three PV inverters to determine the overall efficiency. The tests highlighted the importance of dynamic testing to identify inverters with low dynamic performance, which may even disconnect from the grid in some situations of solar dynamics. One inverter exhibited high dynamic efficiency ($>$ 90%), reducing the overall efficiency by only 0.43% compared to static efficiency. The other two inverters showed reduced dynamic efficiency ($<$ 80%), resulting in a reduction of 2% in overall efficiency compared to static efficiency. While this reduction may seem insignificant, it can play a decisive role in selecting different inverter models for PV system design and may even lead to disqualification of a PV inverter in governmental energy efficiency programs.

Thus, an overall efficiency index contributes to the field of PV systems by providing a unique metric to compare the efficiency of PV inverters. Another implication of the

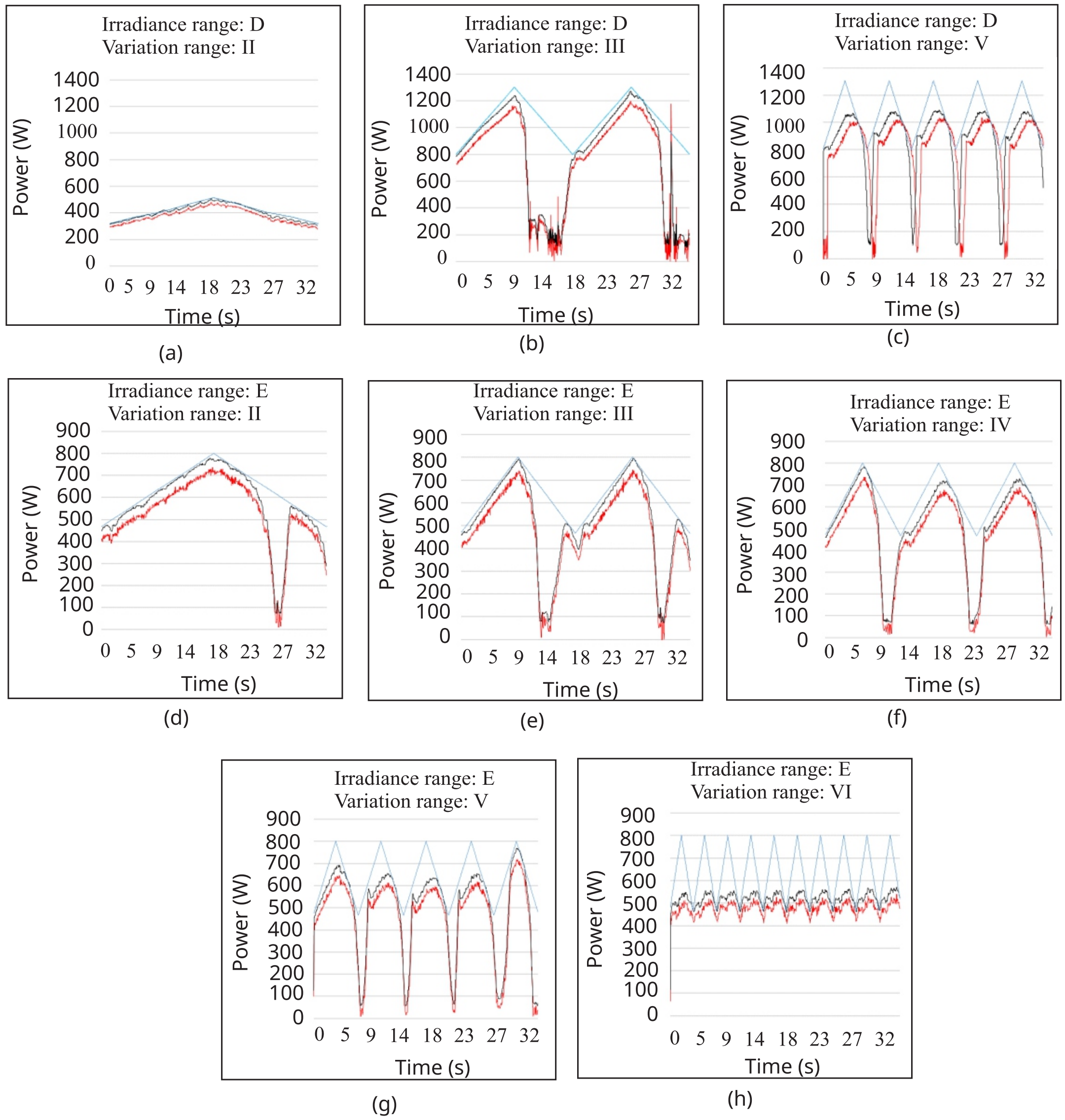

FIGURE 5. Dynamic efficiency tests for inverter A (3 kW): (a) Range D and II; (b) Ranges D and III; (c) Ranges D and V; (d) Ranges E and II; (e) Ranges E and III; (f) Ranges E and IV; (g) Ranges E and IV; (h) Ranges E and VI. Colors: • PV array maximum power; • input dc instant power; • output ac instant power.

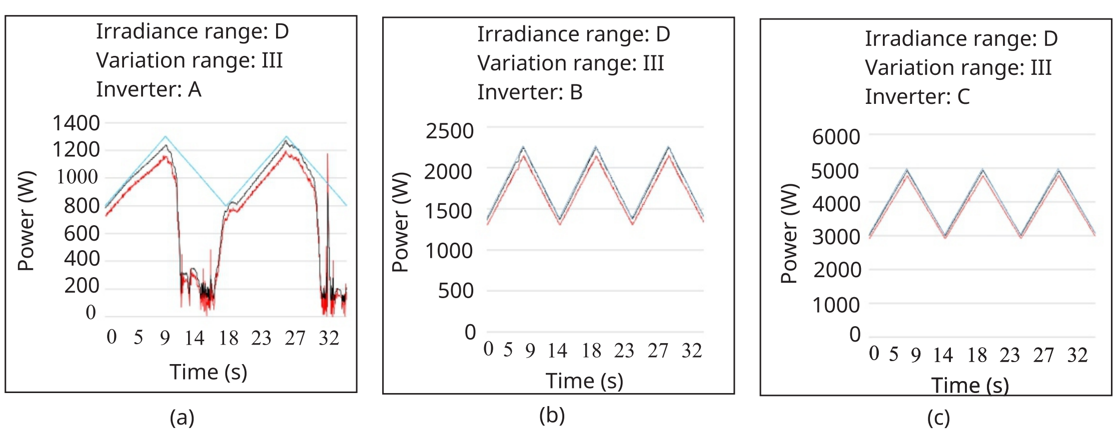

FIGURE 6. Dynamic efficiency tests for inverters in Range D: (a) Inverter A (3 kW); (b) Inverter B (6 kW); (c) Inverter C (12 kW). Colors: • PV array maximum power; • input dc instant power; • output ac instant power.

results obtained is the importance of considering the dynamic efficiency of PV inverters in high-precision simulations. Simulators typically consider irradiance data with a minimum sampling period of one minute, neglecting sub-minute dynamic effects. Therefore, future PV system simulators can incorporate the dynamic MPPT efficiency of inverters to improve their accuracy.

AUTHOR'S CONTRIBUTIONS

FIGUEIRA, H.H.: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization; **SCHERER, F.S.**: Visualization, Writing – Original Draft, Writing – Review & Editing; **BORTOLINI, R.J.F.**: Data Curation, Software, Validation, Writing – Review & Editing; BELLINASO, L.V.: Methodology, Project Administration, Writing – Original Draft, Writing – Review & Editing; **MICHELS, L.**: Conceptualization, Funding Acquisition, Project Administration, Resources, Supervision, Validation, Writing – Review & Editing.

PLAGIARISM POLICY

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BIOGRAPHIES

Henrique Horst Figueira received his B.Sc. (2013), M.Sc. (2016), and Ph.D. (2020) degrees in Electrical Engineering from the Federal University of Santa Maria (UFSM). From 2016 to 2021, he worked as Metrologist, Technical Manager and Commercial Manager at the Photovoltaic Inverters Testing Laboratory in the Smart Grids Institute (INRI-UFSM). Since 2021, he has been working as Hardware Development Engineer at SEG Automotive Germany GmbH, focusing traction inverters for hybrid and electrical vehicles. His main research interests include traction inverters, renewable energy and power electronics.

Fernando Siqueira Scherer received his Bachelor's degree in Electrical Engineering from the Federal University of Santa Maria, Brazil, in 2020. Currently, he is a Master's student at the Federal University of Santa Maria in the Power Electronics and Control Group. His areas of interest include power electronics, control systems, and electric power processing.

Ricardo Jochann Franceschi Bortolini received the B.Sc. in Control and Automation Engineering by Federal University of Santa Maria (UFSM) in 2015, M. Sc. and Dr. in Electrical Engineering from UFSM in 2018 and 2023 respectively. He worked as Technical Manager at the Photovoltaic Inverters Testing Laboratory in the Smart Grids Institute (INRI-UFSM), from 2017 to 2023. Since 2023, he is R&D&I Project Manager at the INRI-UFSM Embrapii unit (Brazilian Company of Research and Industrial Innovation). Besides, he is a researcher at GEPOC and a member of SOBRAEP and IEC. Your main research interests include renewable energy, power electronics, system testing and validation and hardware-in-the-loop.

Lucas Vizzotto Bellinaso received his B.S., M.Sc. and Ph.D. degrees in electrical engineering from the Federal University of Santa Maria (UFSM), in 2012, 2014 and 2017, respectively. Since 2015, he has been with the Power Electronics and Control Group, where he is currently Professor. His research interests include PV systems, power electronics and control applied to renewable energy systems, and safety of PV systems. Additionally, he is currently National Secretary of ABNT/CB-003/CE 003 082, the Brazilian mirror committee of IEC TC 82.

Leandro Michels (S'97 M'08) received the B.S and Ph.D. degrees from the Federal University of Santa Maria (UFSM), Brazil, in 2002 and 2006, respectively, both in electrical engineering. Since 2009 he has been with the Power Electronics and Control Research Group (GEPOC) at UFSM, where he is currently an Associate Professor. He was director of Smart Grids Institute (INRI/UFSM) and of the Unit on Energy and Mobility of Brazilian Company of Research and Industrial Innovation (Embrapii). Dr. Michels is Research Productivity Grant level DT-1A of CNPq. He has works in the field of photovoltaic systems as manager of the laboratory of PV inverters, in working groups to develop of IEC and Brazilian photovoltaic standards, as well as in R&D projects with industry.