Renewable and Sustainable Energy Reviews 92 (2018) 470–477

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A relative power-based adaptive hybrid model for DC/AC average inverter efficiency of photovoltaics systems

Letícia T. Scarabelot[a,b,*], Carlos R. Rambo[a], Giuliano A. Rampinelli[b]

[a] Department of Electrical and Electronic Engineering (EEL), Federal University of Santa Catarina (UFSC), Florianópolis, SC 88040-900, Brazil
[b] Department of Energy and Sustainability (DES), Federal University of Santa Catarina (UFSC), Araranguá, SC 88905-120, Brazil

ARTICLE INFO

Keywords:
Photovoltaic systems
Inverters
DC/AC average efficiency

ABSTRACT

This paper presents the development of methods and mathematical models to determine the DC/AC average efficiency of inverters that allow to optimize estimates of electricity generation of photovoltaic systems. The adaptive hybrid mathematical model of DC/AC average efficiency of inverters of photovoltaic systems proposed in this paper may be composed of three function settings–Linear, Lognormal, and Polynomial–considering the influence of the relative power, which varies with the sizing factor inverter and the DC input voltage. Determining of the average efficiency with a high degree of accuracy guarantees greater reliability in estimating electricity generation of photovoltaic systems. Depending on the specific behavior of each model and topology of inverter, the adaptive hybrid mathematical model determines the fit functions with highest coefficient R^2, and estimates with accuracy the DC/AC average efficiency that represents the operation and dynamic behavior of the inverters.

1. Introduction

Interest in the integration of distributed generation units in the electric power system arose from the growth of incentives to using alternative sources of energy, the technological evolution that resulted in the fall of prices of energy generation systems [1,2], and from environmental pressures [3]. Especially, distributed generation photovoltaic systems have technological maturity, performance, reliability, economic competitiveness and harmonious architectural integration. In this scenario of inserting distributed generation photovoltaic systems, the consumer units also become electrical energy generating units (prosumer units).

The DC/AC inverter is responsible for converting DC electrical energy generated by photovoltaic modules (photovoltaic array or generator) to AC electrical energy, with characteristics and quality for injection in the power grid. Since the technology was developed, the inverters have considerable increases in DC/AC efficiency and safety in energy conversion, achieving efficiencies of 98% in medium powers [4] and high efficiencies even at load levels of 10 or 20% of power nominal [5]. The inverters used in grid connected photovoltaic systems have a maximum power point tracking, anti-island protection, high conversion efficiency, automatic synchronization with the power grid, low harmonic distortion level and power factor close to the unit [5,6]. Most inverters use a two-stage power conversion topology; the first is a DC/AC/DC or DC/DC stage, which is needed to increase the voltage to higher values. The second stage is the DC/AC conversion for power grid connection [7,8].

There are two main classifications of inverter topologies for photovoltaic systems, with or without galvanic isolation [9]. The use of inverter with low or high frequency transformer ensures galvanic isolation [10]. Galvanic isolation solutions offer safety, but also losses in the extra components, so the inverters without galvanic isolation, that is, transformersless inverters, can increase efficiencies by 1–2% [11].

As a safety measure, the first grid-connected photovoltaic systems were designed to operate at low voltages and therefore, required inverters with transformer [12]. Galvanic isolation prevents leakage of current that can cause, for example, degradation of performance, activation of protections, safety difficulties, and problems of electromagnetic compatibility [8]. However, the use of transformerless inverters has some limitations, for example, several thin film modules need protection against leakage currents caused by the parasitic capacitance. In this case, inverters with high frequency transformers are required; thus it is possible to ground the negative pole of the modules avoiding an electrical corrosion, which damages their cells, impairing their performance and service life [13,14]. Transformers are heavy, expensive, and have always been an obstacle for manufacturers to increase the DC to AC efficiency. Currently, photovoltaic systems operate at higher voltages and transformerless inverters predominate in

* Corresponding author at: Department of Electrical and Electronic Engineering (EEL), Federal University of Santa Catarina (UFSC), Florianópolis, SC 88040-900, Brazil.
E-mail address: leticia.scarabelot@posgrad.ufsc.br (L.T. Scarabelot).

https://doi.org/10.1016/j.rser.2018.04.099
Received 3 November 2017; Received in revised form 19 January 2018; Accepted 15 April 2018
1364-0321/

applications [7]. The increasing use of single-phase transformerless inverters is due to lower cost, higher efficiency, smaller size and weight compared with inverters with transformer [8,10,12]. Advances in of power electronics embedded in inverters allowed the rapid development and improvement of all the functions and features of this equipment [15]. The increase in DC voltages brings advantages and allows the use of transformerless inverters, as well as the use of a greater number of photovoltaic modules per strings, fewer circuits and components, including protection and disconnection devices [7,12].

1.1. DC/AC efficiency of inverters

DC/AC conversion efficiency of the inverter (Eq. (1)) is defined as the ratio between the output electric energy of the inverter and tits input electrical energy [16].

$$\eta_{inv} = E_{CA}/E_{CC} = \int P_{CA}.\ dt/\int P_{CC}.\ dt \tag{1}$$

where: E_{CA} is the output electrical energy of the inverter; E_{CC} the input electrical energy of the inverter; P_{CA} the output power of the inverter; P_{CC} the input power of the inverter.

Studies such as Yilmaz and Dincer [15] show that the type of inverters and their losses affect the performance of photovoltaic plants. The DC/AC conversion efficiency is dependent mainly on the relative power of the inverter [5]. The relative power is the ratio between the instantaneous power and nominal power. Additionally, the higher the nominal power of the inverter the lower its losses [15]. The DC input voltage also affects the DC/AC efficiency of the inverter, although this is a dependence often overlooked in the simple mathematical models that represent the electric behavior of the inverter. Tests and assays performed in Sandia Laboratories *(Sandia National Laboratories)* show that the DC/AC efficiency has no significant temperature dependence, the mathematical models being disregarded not to increase the complexity [5].

Mathematical models that consider the instantaneous efficiency of inverters of photovoltaic systems can be found in the scientific literature. These mathematical models describe the dynamic behavior of the inverter and allow estimation of DC/AC instantaneous efficiency depending on the input parameters.

One of the simplest models is proposed by Keating et al. [17]: it proposes a linear interpolation between efficiency samples. Samples can be obtained experimentally or by algebraic methods, modeling and analyzing the theoretical losses of each part of the inverters, Eq. (2).

$$\eta(p) = n_{low} + [(p - p_{low})(\eta_{upp} - \eta_{low})]/(p_{upp} - p_{low}) \tag{2}$$

where: p is the power for which efficiency is evaluated; p_{low} and p_{upp} are the powers to the upper and lower samples, η_{low} and η_{upp} are the efficiency values for the lowest and highest power. For its simplicity, this model presents discontinuities and the need to store the samples in a table [18].

Jantsch, Schimidt and Schmid [19], present a model based on the approximation of the efficiency curve, using a polynomial function, Eq. (3).

$$\eta(p) = p/[p+(k_0 + k_1 p + k_2 p^2)] \tag{3}$$

where: k_0, k_1 and k_2 are coefficients obtained through the curve fitting.

Driesse, Jain and Harrison [20] also present a simple model, Eq. (4), where efficiency is approximated by a second-order function.

$$\eta(p) = \alpha_0 + \alpha_1 p + \alpha_2 p^2 \tag{4}$$

where: α_0, α_1 and α_2 are coefficients obtained by curve fitting.

Another model is proposed by Dupont et al. [21], which represents the efficiency curve as a rational function, Eq. (5).

$$\eta(p) = (\alpha_1 p + \alpha_0)/(p^2 + \beta_1 p + \beta_0) \tag{5}$$

Because it has additional coefficients, this model presents good representativeness for the entire power range.

Table 1
Description of the studied inverters.

Inverter	Description
SMA TL	Transformerless
SMA TLH5	Transformerless
SMA US	Low Frequency Transformer
SMA HF	High Frequency Transformer
Fronius TL	Transformerless
Growatt TL	Transformerless

The output power is highly dependent on the input power, regardless of the topology of the inverter. Thus, neglecting the dependence of the DC input voltage on the inverter efficiency, Bakhshi, Sadeh and Mosaddegh [22] propose a model to express the instantaneous efficiency curve as a function of input power, as shown in Eq. (6).

$$\eta_{inv} = A + B.\ P_{dc,pu} + C/P_{dc,pu} \tag{6}$$

where A, B and C must be determined. For this, three pairs of ($\eta_{inv} - P_{dc,pu}$) are required. These pairs can be extracted from the efficiency curve of the inverter available in the technical data document provided by the suppliers. The efficiency curve of the inverter generally has three voltage levels: low, nominal, and high. Next, the three parameters (A, B and C) can be determined by solving a linear system of three equations with three unknowns [22].

The DC input voltage also influences the instantaneous efficiency of the inverter, and Rampinelli, Krenzinger and Romero [5] propose the modified Jantsch, Schimidt and Schmid [19] model to consider the relative power and DC input voltage, according to Eq. (7).

$$\eta_{inv} = (P_{AC}/P_N)/(P_{AC}/P_N\ ) + (A + B.\ (P_{AC}/P_N) + C.\ (P_{AC}/P_N)^2) \tag{7}$$

$$A = K_{0_{VDC0}} \pm S_0 V_{DC} \tag{8}$$

$$B = K_{1_{VDC0}} \pm S_1 V_{DC} \tag{9}$$

$$C = K_{2_{VDC0}} \pm S_2 V_{DC} \tag{10}$$

where: P_N is the nominal power of the inverter; P_{AC} Is the output power of the inverter; $K_{0_{VDC0}}$, $K_{1_{VDC0}}$, $K_{2_{VDC0}}$ are linear voltage coefficients; S_0 , S_1 , and S_2 are voltage angular coefficients.

Each coefficient is described by two voltage coefficients: the linear voltage coefficient and the voltage angular coefficient. The voltage coefficients are determined from the fitting between the theoretical curve, which in this case is linear, and the power coefficients are determined at different DC input voltages.

Dupont et al. [21] suggest that for drives in which the DC input voltage has a linear relationship, one can then choose quadratic functions K_0, K_1 and K_2 . In addition, Eq. (11), Driesse, Jain and Harrison [20] also modified the Jantsch, Schimidt and Schmid model [19], where the quadratic term is replaced by the inverse DC input voltage, representing the dependence of this parameter.

$$\eta(p, v_{in}) = p/(p + b_0(v_{in}) + b_1(v_{in})p + b_2(v_{in})p^2) \tag{11}$$

where:

$$b_0(v_{in}) = b_{0,0} + b_{0,1}(v_{in}-1) + b_{0,2}((1/v_{in})-1) \tag{12}$$

$$b_1(v_{in}) = b_{1,0} + b_{1,1}(v_{in}-1) + b_{1,2}((1/v_{in})-1) \tag{13}$$

$$b_2(v_{in}) = b_{2,0} + b_{2,1}(v_{in}-1) + b_{2,2}((1/v_{in})-1) \tag{14}$$

In the Guerrero-Perez [23] study, a model was developed to calculate efficiency as presented in Eq. (15).

$$\eta_{inv} = 1-((P_{AC}/(V_{AC}^{RMS})^2)\bullet(k_1 + k_2/V_{DC}) + (1/V_{AC}^{RMS})\bullet(k_3 + k_4/V_{DC}) + k_5/P_{AC}) \tag{15}$$

where the parameters k_i can be estimated by representative values of

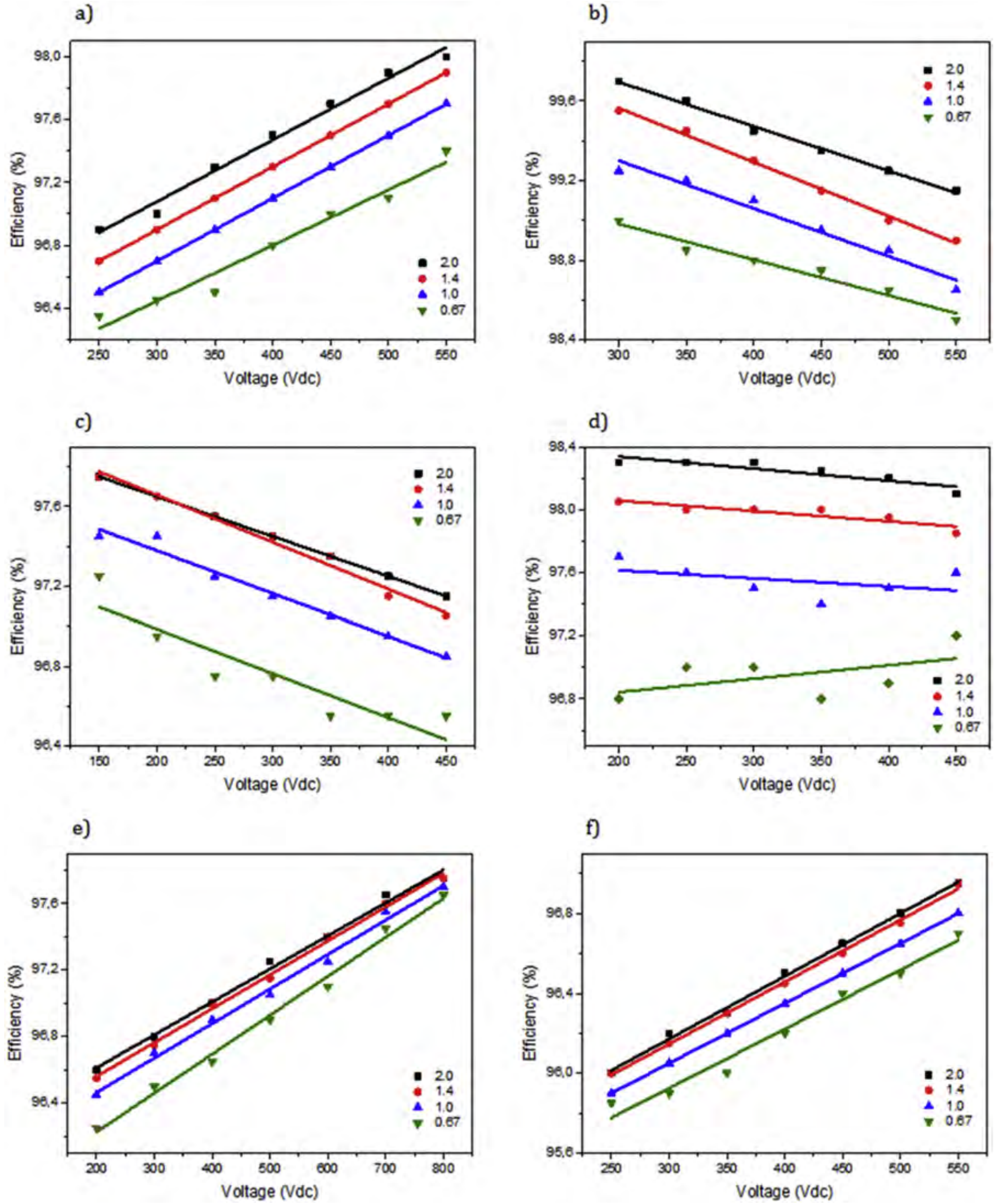

Fig. 1. Inverters in SFI's 2.0, 1.4, 1.0 e 0.67: (a) SMA TL, (b) SMA TLH5, (c) SMA US, (d) SMA HF, (e) Fronius TL, (f) Growatt TL.

the inverter technical data [23].

In Bakhshi and Sadeh [24] work, a model was used to calculate the efficiency of the inverter that only involves the technical data of the manufacturers. The dependence of DC voltage and temperature is not taken into account in the calculation. Eq. (16) shows the correlation used to estimate the efficiency of the inverter:

$$\eta_{inv} = P_{inv,ac}/P_{inv,dc} = P_{inv,ac}/(P_{inv,ac} + (k_o + k_1 P_{inv,ac} + k_2 P_{inv,ac}^2)) \tag{16}$$

where $P_{inv,dc}$ (pu) e $P_{inv,ac}$ (pu) are the input and output powers, respectively. The parameters k_o, k_1 and k_2 can be determined using the "least square error" and applying at least three pairs of (η_{inv}_$P_{inv,ac}$) or (η_{inv}_$P_{inv,dc}$) in the rated input power [24].

The expression for the output power as a function of the input power. Is represented by Eq. (17).

$$P_{inv,ac} = (-(1+k_1) \pm \sqrt{(1+k_1)^2 - 4k_2(k_o - P_{inv,dc})})/2k_2 \tag{17}$$

$P_{inv,ac}$ should always be positive and where the value of the first term of the numerator is negative in Eq. (17), the positive sign of the second term should be considered [24].

In Roberts, Zevallos and Cassula [2], a model was implemented that is able to represent the efficiency of the inverter in the whole range of operating conditions, is simple to integrate in simulation tools, and that produces results with good precision. The efficiency of the inverter referred to the input power is shown in Eq. (18).

$$\eta_{inv} = (p - p_o - kp^2)/p \tag{18}$$

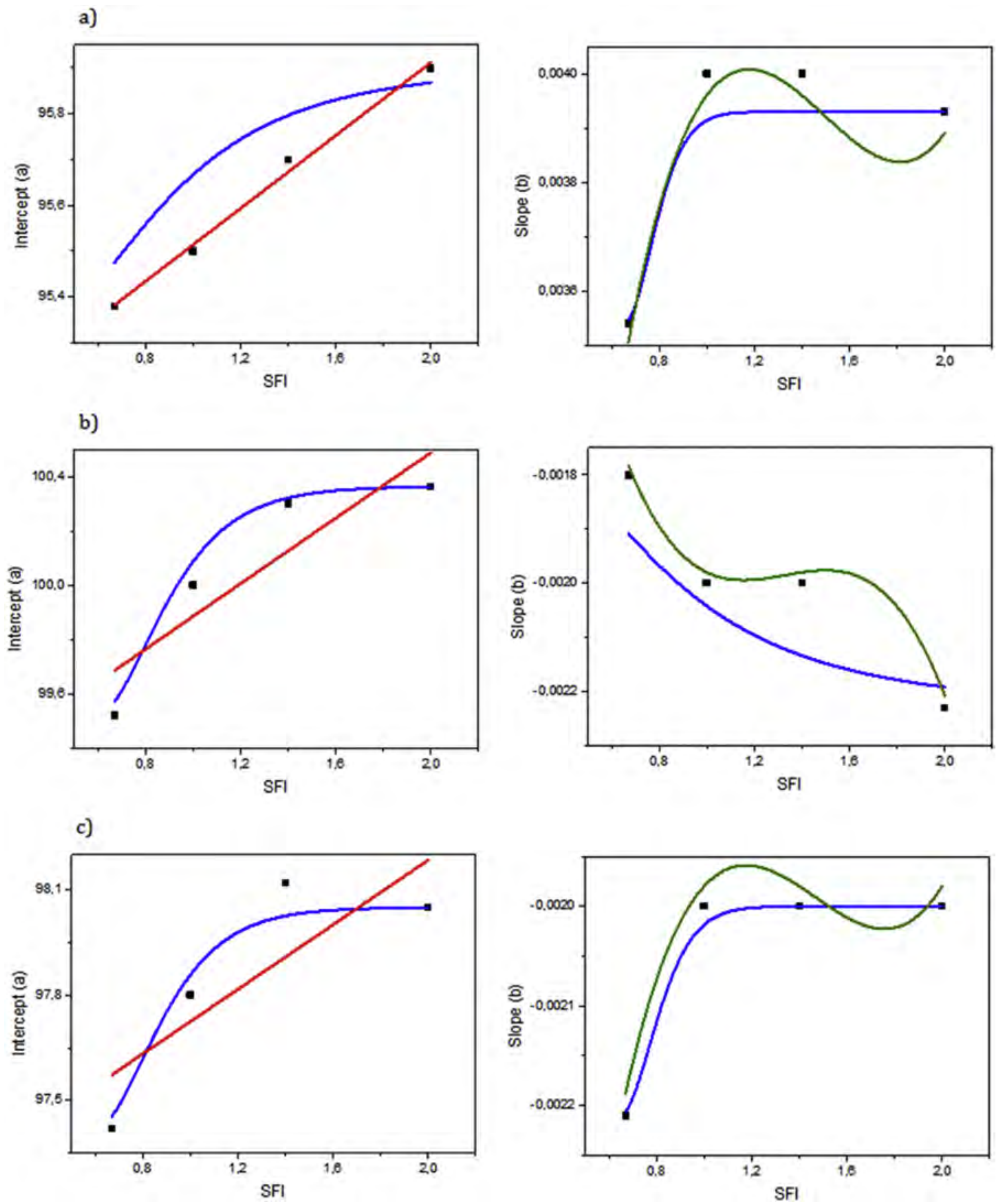

Fig. 2. Fitting functions for the inverters: (a) SMA TL, (b) SMA TLH5, (c) SMA US, (d) SMA HF, (e) Fronius TL, (f) Growatt TL.

where p is the load fraction given by $p = P_{input}/P_{dc,rated}$; P_{input} the DC power input; $P_{dc,rated}$ the rated power DC and,

$$p_o = (1/99)(10/\eta_{10} - 1/\eta_{100}-9) \tag{19}$$

$$k = (1/\eta_{100}) - p_o - 1 \tag{20}$$

η_{10} and η_{100} are the inverter efficiency 10% and 100% of rated power. The parameters are p_o and k are characteristics of each inverter type [2].

The inverters operate with a floating input power supplied by the photovoltaic array and, therefore, the conversion efficiency must be measured as a function of the weights of the likely powers representing the values of the solar irradiance. This approach with different weights for different ranges of solar irradiation resulted in two basic models of the weighted conversion efficiency: the European efficiency (Eq. (21)) and the Californian efficiency, defined by solar energy program of the California Energy Commission (CEC), Eq. (22).

$$\eta_{EU} = (0,\ 03\eta_{5\%}) + (0,\ 06\eta_{10\%}) + (0,\ 13\eta_{20\%}) + (0,\ 1\eta_{30\%}) + (0,\ 48\eta_{50\%}) + (0,\ 2\eta_{100\%}) \tag{21}$$

$$\eta_{CEC} = (0,\ 04\eta_{10\%}) + (0,\ 05\eta_{20\%}) + (0,\ 12\eta_{30\%}) + (0,\ 21\eta_{50\%}) + (0,\ 53\eta_{75\%}) + (0,\ 05\eta_{100\%}) \tag{22}$$

where: $\eta_{5\%}$, $\eta_{10\%}$, $\eta_{20\%}$, $\eta_{30\%}$, $\eta_{50\%}$, $\eta_{75\%}$, and $\eta_{100\%}$ are the values of conversion efficiency, respectively in 5%, 10%, 20%, 30%, 50%, 75%, and

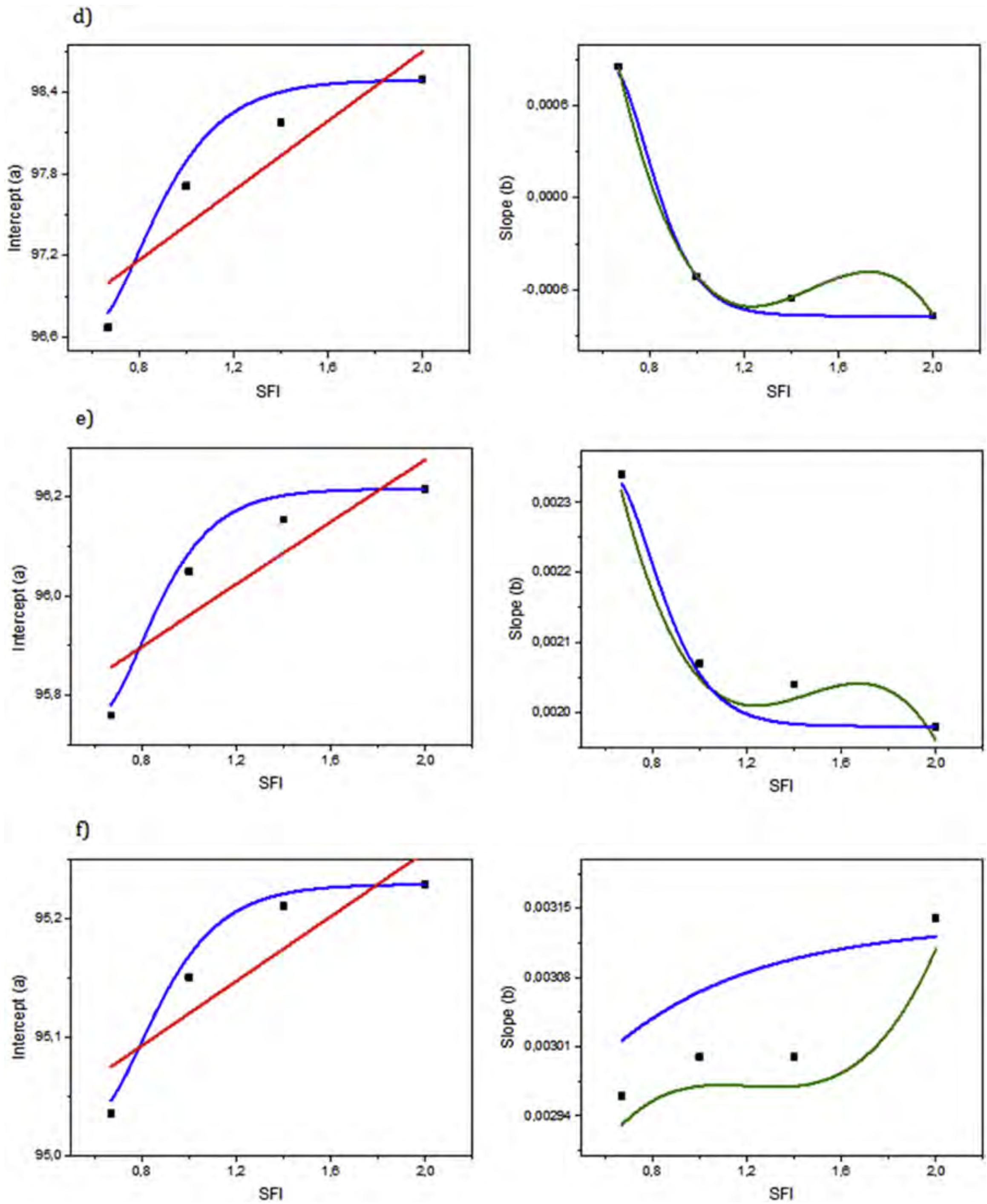

Fig. 2. (*continued*)

100% of the nominal power inverter.

These two models consider the distribution of solar irradiation during the entire annual sun time and prioritize the bands with various weight factors [25], assigning weights to DC/AC efficiency at different levels of load or relative power. European efficiency considers a low irradiance profile, and CEC efficiencies is based on solar radiation from California, in other words, a high level of irradiance.

Datasheets of inverters of the distributed generation photovoltaic systems commonly show maximum efficiency and European efficiency [26]. However, the weighted efficiencies do not consider the influence of the DC input voltage and the sizing factor of the inverter. The inverters present DC/AC efficiency curves that depend on relative power, DC input voltages and topology of the inverter. In different sizing factors of the inverters, the coefficients of the European and CEC efficiency are necessarily different.

The sizing factor inverter (SFI) is the ratio between the inverter nominal power and the array or generator photovoltaic in standard tests conditions, as shown in Eq. (23).

$$SFI = P_{INV}/P_{FV} \tag{23}$$

where: SFI is the sizing factor inverter; P_{INV} the nominal power of the inverter; P_{FV} the power of the photovoltaic generator in the standard tests conditions.

The optimization of the SFI for a given locality has been the subject of several studies and is of fundamental importance to guarantee maximum performance of the photovoltaic system [6,27]. For

Table 2
Fitting functions that correlate the angular and linear coefficients and the sizing factor of the inverter.

Inverter	a = f(SFI)		b = f(SFI)	
SMA TL	Linear	E: 95.11541 F: 0.3981	Pol^3	A: 6.1645E-5 B: 0.00855 C: -0.00599 D: 0.00133
SMA TLH5	LogNormal	$(a \text{ or } b)_0$: 100.363 L: -0.46803 w: 0.35167 SFI.k: 0.67	Pol^3	A: 1.80E-5 B: -0.00469 C: 0.0036 D: -9.0332E-4
SMA US	LogNormal	$(a \text{ or } b)_0$: 98.05 L: -0.33241 w: 0.33197 SFI.k: 0.67	LogNormal	$(a \text{ ou } b)_0$: -0.002 L: -6.9219E-5 w: 0.20024 SFI.k: 0.67
SMA HF	LogNormal	$(a \text{ or } b)_0$: 98.4923 L: -1.00943 w: 0.35106 SFI.k: 0.67	Pol^3	A: 0.01057 B: -0.023399 C: 0.01666 D: -0.00375
Fronius TL	LogNormal	$(a \text{ or } b)_0$: 98.21607 L: -0.22979 w: 0.31449 SFI.k: 0.67	Pol^3	A: 0.00426 B: -0.00483 C: 0.00339 D: -7.76411E-4
Growatt TL	LogNormal	$(a \text{ or } b)_0$: 95.2285 L: -0.10337 w: 0.33788 SFI.k: 0.67	Pol^3	A: 0.00246 B: 0.00129 C: -0.00108 D: 2.97281E-4

Table 3
The maximum, CEC, European and range of this work efficiencies.

Inverter	Maximum Ef.[a] (%)	CEC Ef.[b] (%)	European Ef.[b] (%)	Range of this work (%)
SMA TL	97.6	97.055	96.853	98.0–96.35
SMA TLH5	98.7	98.360	98.179	99.7–98.5
SMA US	95.5	95.573	94.666	97.75–96.55
SMA HF	96.6	96.748	96.530	98.3–96.8
Fronius TL	98	96.933	96.167	97.75–96.25
Growatt TL	97.5	96.443	95.913	96.95–95.85

[a] datasheet.
[b] SAM.

optimization, high-efficiency inverters are desirable not only at rated power, but at all load levels, improving weighted efficiency. Therefore, this work presents a model that takes into account the input DC voltage and SFI for determining the average DC/AC efficiency.

2. Materials and methods

A mathematical model was developed to determine the average DC/AC efficiency as a function of input DC voltage and SFI, according to Eq. (24).

$$\eta_{med} = f(Pr_{SFI}, V_{dc}) \tag{24}$$

The Solar Advisor Model –(SAM software) developed by the National Renewable Energy Laboratory –(NREL) of the Department of Energy/USA, was used for the design and simulation of photovoltaic systems. The parameter used for the analysis is the average annual DC/AC efficiency of the inverters of different technologies. For each inverter technology, photovoltaic systems were simulated considering different DC input voltages and different sizing factors. We used solar radiation data from Florianópolis/SC, Brazil.

From the results of the simulation were determined the average DC/AC efficiency for the sizing factors inverter of 2.0, 1.4, 1.0 and 0.67 for each inverter technology. For each SFI the linear correlation between the average DC/AC efficiency and the DC voltage, and the extracted linear coefficients (a) and the angle coefficients (b) of Eq. (25) were determined:

$$\eta_{med} = a + b.\ Vdc \tag{25}$$

A correlation between the linear and angular coefficients (a and b)- and SFI was determined for each inverter technology. The linear and angular coefficients are a function of the SFI, according to Eqs. 26 and 27.

$$a = f(SFI) \tag{26}$$

$$b = f(SFI) \tag{27}$$

From the results and the correlations and using interpolation methods, maps of the dynamic behavior of the average DC/AC efficiency of the inverter in different sizing factors and different input DC voltages were generated. The maps show and emphasize the operating ranges where one can optimize the inverter performance from the average DC/AC efficiency.

The inverters described in Table 1, transformerless, TL model (manufacturers: SMA, Fronius and Growatt), and TLH5 model (manufacturer SMA), were simulated for different sizing factors (SFI) and all possible input DC voltages. The same procedure was applied for the inverters with high frequency transformers model HF and inverters with low frequency transformers model US (manufacturer SMA).

3. Results and discussion

Fig. 1(a-f) shows the correlation between average DC/AC efficiency and DC input voltage for different SFIs of each PV system inverter. From this correlation, which is linear, the coefficients, linear and angular, of each configuration (SFI and inverter) are determined.

Fig. 2(a-f) shows the correlations between linear and angular coefficients determined as a function of the sizing factor of the inverters. The functions with the best fit and their respective coefficients were determined for each inverter. In this paper, we propose the adaptive hybrid mathematical model of average DC/AC efficiency of inverters of photovoltaic systems that can be composed of three fitting functions (Linear, LogNormal, Polynomial). Depending on the specific behavior of each inverter, the adaptive hybrid mathematical model is fitted with greatest determination coefficient R^2. The adaptive hybrid mathematical model of average DC/AC efficiency of inverters of photovoltaic systems proposed in this paper considers the influence of relative power, which varies with the sizing factor, and the DC input voltage.

For the correlation between the coefficient (α) and the SFI, linear functions (Eq. (28)) and logarithmic functions (LogNormal, Eq. (29)) were plotted while for the correlation between the coefficient (b) and the SFI, polynomial functions (Eq. (30)) and logarithmic functions (LogNormal) were plotted.

$$f1 = E + F.\ SFI \tag{28}$$

$$f2 = f2_0 + (L/\sqrt{2\pi}.\ w.\ SFI).e^{\frac{-\left[\ln\frac{SFI}{SFI.k}\right]^2}{2w^2}} \tag{29}$$

$$f3 = A + B.\ SFI + C.\ SFI^2 + D.\ SFI^3 \tag{30}$$

For the SMA TL Inverter, Fig. 2(a), the function to describe the correlation between the linear coefficient (a) and the sizing factor inverter is a linear function, while for the other inverters, the best fitting function between the coefficient (a) and SFI is the LogNormal function. For the inverter SMA US, Fig. 2(c), the fitting function between the angular coefficient (b) and the sizing factor inverter is the LogNormal correlation, while for the other inverters the best-fit function between the coefficient (b) and SFI is the Pol^3 correlation. Table 2 presents the fitting functions that correlate the coefficients, linear and angular, and the sizing factor inverter for each simulated inverter technology.

The correlations vary according to inverter technology and manufacturer. The combinations are described in Eqs. 31, 32, 33, and 34. As

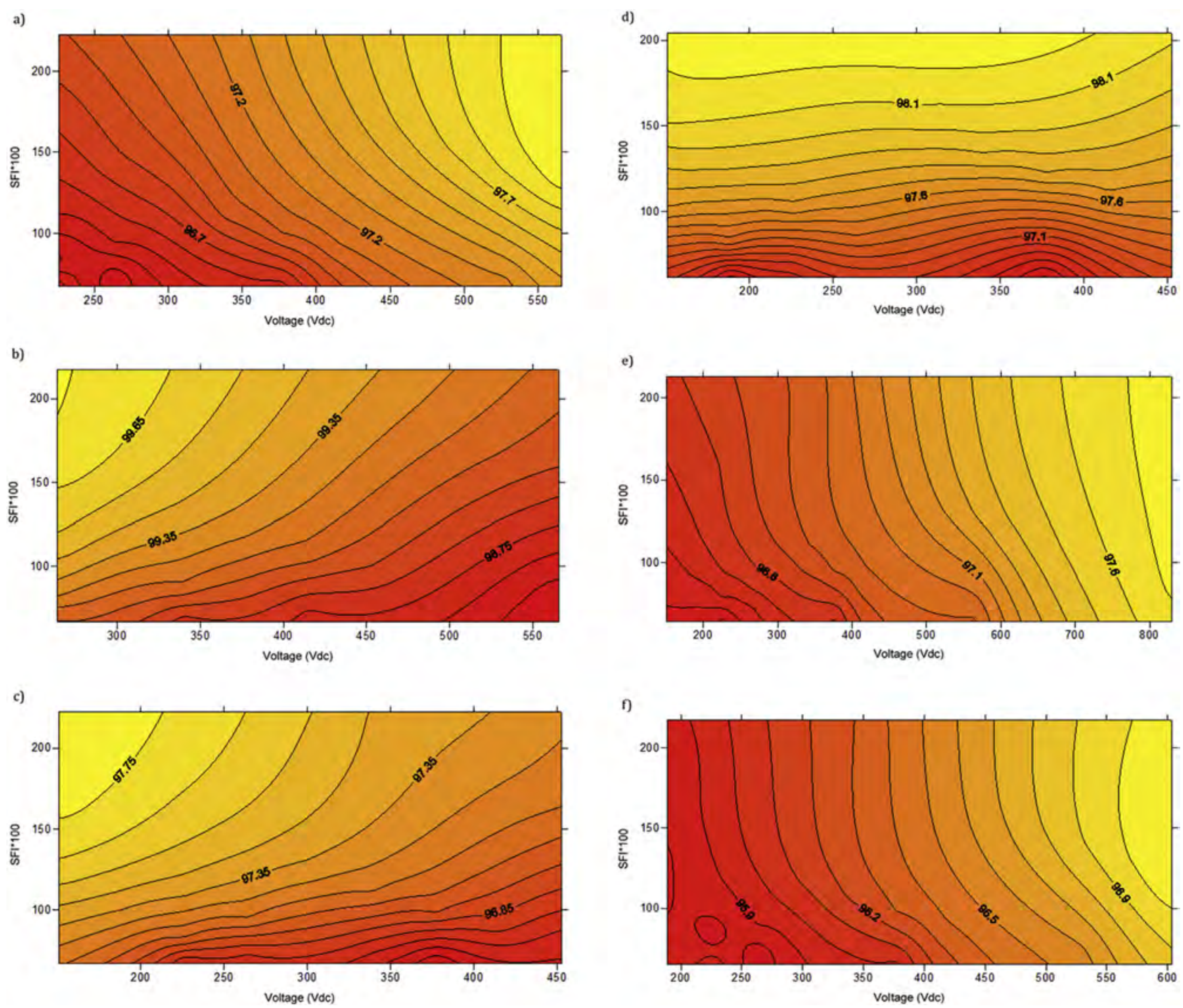

Fig. 3. Average efficiency maps: a) SMA TL, b) SMA TLH5, c) SMA US, d) SMA HF, e) Fronius TL, f) Growatt TL.

proposed in this paper, this model is called adaptive hybrid mathematical model of average DC/AC efficiency of inverters of photovoltaic systems.

$$\eta_{med} = f2 + f2.Vdc \tag{31}$$

$$\eta_{med} = f1 + f3.Vdc \tag{32}$$

$$\eta_{med} = f2 + f3.Vdc \tag{33}$$

$$\eta_{med} = f1 + f2.Vdc \tag{34}$$

Table 3 presents the values of maximum efficiency, CEC, and European efficiency, and the range of the average efficiency as a function of the sizing factor inverter and DC input voltage that were obtained from computational simulations. The CEC and European efficiency of transformerless and single-phase inverters reported in the literature are in the 96–98% range [28]. The maximum, European and CEC efficiencies are the data generally found in the datasheet of the inverter. However, manufacturers have efficiency curves as a function of the relative power for 3 DC input voltages [26].

When considering the Brazilian solar radiation profile, the SFI, and the influence of DC input voltage, a range of average efficiencies can be observed, ranging from 1% to 2%. This information of average efficiencies as a function of the sizing factor inverter and DC input voltage are more representative of the inverter operation than its maximum, CEC, or European efficiencies. In many mathematical models of grid connected photovoltaic systems, the DC/AC efficiency of the inverter is represented by a constant factor, assuming a linear relation to its operating range. However, the efficiency indicates the fraction of DC input power that is transferred to the AC output and this efficiency depends on the DC input voltage and the relative power [2].

The comparison between inverters using the maximum efficiency is less representative since it does not take into account the fact that the inverter does not operate all the time at nominal power.

CEC and European efficiencies do not take into account the voltages admissible by the inverter and the profile of solar radiation is given to specific regions.

Currently the use of inverters with transformers is avoided due to cost, size and efficiency [8,13]. However, for example, the SMA US and HF models exhibit a range of average efficiencies compatible with other models. One advantage is that inverters with transformer can be used with photovoltaic modules of thin films. Commonly, the high frequency transformer is used on the DC side and the low frequency transformer on the AC side [9]. The average DC/AC efficiencies were determined from the simulations of the photovoltaic systems. Dynamic maps of the average DC/AC efficiency were developed considering different sizing factors and DC input voltages for each inverter technology. Fig. 3(a-f) shows maps for each inverter technology, where the highest efficiencies are represented by yellow color and the lowest efficiencies are displayed in red.

The maps of Fig. 3(a), (e) and (f) show higher mean efficiencies at higher voltages, independent of the manufacturer the transformerless inverters have higher efficiency curves at high DC voltages. The TLH5 model, Fig. 3(b), is the topology H5 patented by SMA TECHNOLOGIE AG [11]. This model brings some changes to the conventional TL model and presents better average efficiencies at low DC voltages. In Fig. 3(c) the SMA US model, inverter topology with low-frequency transformer, presents better average efficiencies at low voltages; for the SMA HF model, Fig. 3(d), with high-frequency transformer, the efficiency is shown to be more dependent on SFI than on DC voltages, presenting higher efficiencies for higher SFIs.

From the efficiency maps as a function of the DC input voltage and the sizing factor inverter, it is possible to determine the inverter optimized operation condition and maximize the conversion of electric energy.

The method proposed here can be used in laboratory tests for the electrical characterization of inverters. The coefficients and functions of the proposed model were determined in the specific tests of inverters with controllable test conditions. The flexibility of the proposed hybrid model allows adjusting the most suitable functions for each operating condition and inverter topology. For each inverter tested, the adjustment of the coefficients and functions allows estimating the actual average efficiency for the inverter topology and operating condition.

4. Conclusions

In particular, it was developed and presented an adaptive hybrid mathematical model that considers the influence of the relative power, which varies with the SFI and the DC input voltage to the South of Brazil radiation profile. From the fit functions for each manufacturer and topology of the inverter, it was possible to develop dynamic maps that represent the behavior of the DC/AC average efficiency of operation under different conditions of SFI and DC input voltage. The determination of the average efficiency with a high degree of accuracy and precision guarantees greater reliability in the estimation of electricity generation of photovoltaic systems. From the results it was verified that the average efficiencies determined in this study have efficiencies ranging between 1% and 2%. The adaptative hybrid mathematical model allows precision and accuracy to determine the DC/AC average efficiency of inverters of photovoltaic systems.

Acknowledgements

The authors greatfully thank the National Council for Scientific and Technological Development (CNPq, Brazil), (153539/2016-0) for scholarships and financial support. The Electric Energy Technology Nucleus (NTEEL) at UFSC is also well acknowledged.

References

[1] Faranda RS, Hafezi H, Leva S, Mussetta M, Ogliari E. The optimum PV plant for a given solar DC/AC converter. Energies 2015;8:4853–70. http://dx.doi.org/10.3390/en8064853.

[2] Roberts JJ, Zevallos AAM, Cassula AM. Assessment of photovoltaic performance models for system simulation. Renew Sustain Energy Rev 2017;72:1104–23. http://dx.doi.org/10.1016/J.RSER.2016.10.022.

[3] Davi GA, Caamano-Martin E, Ruther R, Solano J. Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil. Energy Build 2016;120:19–29. http://dx.doi.org/10.1016/j.enbuild.2016.03.058.

[4] Kratzenberg MG, Deschamps EM, Nascimento L, Ruther R, Zurn HH. Optimal photovoltaic inverter sizing considering different climate conditions and energy prices. Energy Procedia 2014;57:226–34. http://dx.doi.org/10.1016/J.EGYPRO.2014.10.027.

[5] Rampinelli GA, Krenzinger A, Romero FC. Mathematical models for efficiency of inverters used in grid connected photovoltaic systems. Renew Sustain Energy Rev 2014;34:578–87. http://dx.doi.org/10.1016/J.RSER.2014.03.047.

[6] Mahela OP, Shaik AG. Comprehensive overview of grid interfaced solar photovoltaic systems. Renew Sustain Energy Rev 2017;68:316–32. http://dx.doi.org/10.1016/J.RSER.2016.09.096.

[7] Cortajarena JA, Barambones O, Alkorta P, De Marcos J. Sliding mode control of grid-tied single-phase inverter in a photovoltaic MPPT application. Sol Energy 2017;155:793–804. http://dx.doi.org/10.1016/J.SOLENER.2017.07.029.

[8] Faraji F, Mousavi GSM, Hajirayat A, Birjandi AAM, Al-Haddad K. Single-stage single-phase three-level neutral-point-clamped transformerless grid-connected photovoltaic inverters: topology review. Renew Sustain Energy Rev 2017;80:197–214. http://dx.doi.org/10.1016/J.RSER.2017.05.181.

[9] Freddy TKS, Rahim NA, Hew Wooi-Ping, Che Hang Seng. Comparison and analysis of single-phase transformerless grid-connected PV inverters. IEEE Trans Power Electron 2014;29:5358–69. http://dx.doi.org/10.1109/TPEL.2013.2294953.

[10] Islam M, Mekhilef S, Hasan M. Single phase transformerless inverter topologies for grid-tied photovoltaic system: a review. Renew Sustain Energy Rev 2015;45:69–86. http://dx.doi.org/10.1016/j.rser.2015.01.009.

[11] Kerekes T, Teodorescu R, Rodriguez P, Vazquez G, Aldabas E. A New high-efficiency single-phase transformerless PV inverter topology. IEEE Trans Ind Electron 2011;58:184–91. http://dx.doi.org/10.1109/TIE.2009.2024092.

[12] Meneses D, Blaabjerg F, García O, Cobos JA. Review and comparison of step-up transformerless topologies for photovoltaic AC-module application. IEEE Trans Power Electron 2013;28:2649–63. http://dx.doi.org/10.1109/TPEL.2012.2227820.

[13] Shen J-M, Jou H-L, Wu J-C. Novel transformerless grid-connected power converter with negative grounding for photovoltaic generation system. IEEE Trans Power Electron 2012;27:1818–29. http://dx.doi.org/10.1109/TPEL.2011.2170435.

[14] Aarich N, Bennouna A, Erraissi N, Raoufi M, Akhsassi M, Sobhy I. Performance of different silicon PV technologies based on experimental measurements: a case study in Marrakech. Int Renew Sustain Energy Conf 2016:1064–9. http://dx.doi.org/10.1109/IRSEC. 2016.7983952.

[15] Yilmaz S, Dincer F. Impact of inverter capacity on the performance in large-scale photovoltaic power plants – A case study for Gainesville, Florida. Renew Sustain Energy Rev 2017;79:15–23. http://dx.doi.org/10.1016/J.RSER.2017.05.054.

[16] Electrotechnical CI. IEC 61863: Photovoltaic systems - Power conditioners - Procedure for measuring efficiency 1999:26; 1999.

[17] Keating L, Mayer D, McCarthy S, Wrixon G. Concerted action on computer modeling simulation. In: Proceedings of the Tenth E.C. Photovoltaic Solar Energy Conference, Dordrecht: Springer Netherlands, 1991, p. 1259–1265. doi:10.1007/978-94-011-3622-8_317.

[18] Dupont FH, Bertomeu JZ, Rech C, Pinheiro JR. Mathematical efficiency modeling of static power converters. In: Proceedings of the 13th Brazilian Power Electronics Conference 1st Southern Power Electronics Conference, IEEE, 2015, p. 1–6. doi:10.1109/COBEP.2015.7420263.

[19] Jantsch M, Schimidt H, Schmid J. Results of the concerted action on power conditioning and control. In: Proceedings 11th European Photovoltaic Solar Energy Conference Montreux Switzerland, 1992, p. 1589–1593.

[20] Driesse A, Jain P, Harrison S. Beyond the curves: Modeling the electrical efficiency of photovoltaic inverters. 2008 In: Proceedings of the 33rd IEEE Photovolatic Specialist Conference, IEEE, 2008, p. 1–6. doi:10.1109/PVSC.2008.4922827.

[21] Dupont FH, Zaragoza J, Rech C, Pinheiro JR. A new method to improve the total efficiency of parallel converters. In: Proceedings of the Brazilian Power Electronics Conference, IEEE, 2013, p. 210–215. doi:10.1109/COBEP.2013.6785117.

[22] Bakhshi R, Sadeh J, Mosaddegh H-R. Optimal economic designing of grid-connected photovoltaic systems with multiple inverters using linear and nonlinear module models based on Genetic Algorithm. Renew Energy 2014;72:386–94. http://dx.doi.org/10.1016/J.RENENE.2014.07.035.

[23] Guerrero-Perez J, De Jodar E, Góamez-Lázaro E, Molina-Garcia A. Behavioral modeling of grid-connected photovoltaic inverters: development and assessment. Renew Energy 2014;68:686–96. http://dx.doi.org/10.1016/J.RENENE.2014.02.022.

[24] Bakhshi R, Sadeh J. A comprehensive economic analysis method for selecting the PV array structure in grid–connected photovoltaic systems. Renew Energy 2016;94:524–36. http://dx.doi.org/10.1016/J.RENENE.2016.03.091.

[25] Ongun İ, Özdemir E. Weighted efficiency measurement of PV inverters: introducing η İZMİR. J Optoelectron Adv Mater 2013;15(6):550–4.

[26] Pinto A, Zilles R, Almeida M. Eficiência brasileira de inversores para sistemas fotovoltaicos conectados à rede. Av En Energ Renov Y Medio Ambient 2011:15.

[27] Rodrigo PM, Velazquez R, Fernandez EF. DC/AC conversion efficiency of grid-connected photovoltaic inverters in central Mexico. Sol Energy 2016;139:650–65. http://dx.doi.org/10.1016/J.SOLENER.2016.10.042.

[28] Gu B, Dominic J, Lai J-S, Chen C-L, LaBella T, Chen B. High reliability and efficiency single-phase transformerless inverter for grid-connected photovoltaic systems. IEEE Trans Power Electron 2013;28:2235–45. http://dx.doi.org/10.1109/TPEL.2012.2214237.