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

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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

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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