Renewable and Sustainable Energy Reviews 34 (2014) 578–587

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

# Mathematical models for efficiency of inverters used in grid connected photovoltaic systems

G.A. Rampinelli [a], A. Krenzinger [b], F. Chenlo Romero [c]

[a] Federal University of Santa Catarina (UFSC), Rodovia Governador Jorge Lacerda, 3201 Araranguá, SC, Brazil
[b] Federal University of Rio Grande do Sul (UFRGS), Avenida Bento Gonçalves, 9500 Porto Alegre, RS, Brazil
[c] Research Centre for Energy, Environment and Technology (CIEMAT), Avenida Complutense, 22, Madrid, Spain

ARTICLE INFO

*Article history:*
Received 16 November 2013
Received in revised form
28 February 2014
Accepted 9 March 2014
Available online 4 April 2014

*Keywords:*
Solar energy
Grid connected photovoltaic system
Inverters
Software

ABSTRACT

In order to perform a reliable simulation of a photovoltaic system is crucial to know the electrical and thermal characteristics of each component that will be modeled by mathematical models that describe the system operation. This paper presents the development of mathematical models that characterize the inverter used in grid-connected photovoltaic systems. The mathematical models were fitted from experimental tests and they are suitable to be used in computer simulation software. The tests were performed on a set of inverters commercially available at Solar Energy Laboratory at Federal University of Rio Grande do Sul (UFRGS, Brazil) and at Photovoltaic Solar Energy Laboratory at Research Centre for Energy, Environment and Technology (CIEMAT, Spain). From the measured data it was calculated fitting coefficients to the efficiency curve of several inverters. In order to use these mathematical models for simulating other inverters, their own coefficients have to be experimentally determined and entered into the data base of the software in order to provide a full detailed computer simulation.


**Contents**



## 1. Introduction

The evaluation of a grid connected photovoltaic system can be accomplished through a long time or short time monitoring system [1]. It is fundamental to investigate and emphasize the importance of the grid connected PV system regarding the intermittent nature of renewable generation, and the characterization of PV generation with regard to grid code compliance [2]. Software is an important tool for simulation, design, characterization and analysis of photovoltaic systems. The monitoring equipment depends on experimental measurements and time to perform the system analysis in a short time, while computer software has the capability to perform a number of simulations of

*E-mail addresses:* giuliano.rampinelli@ufsc.br (G.A. Rampinelli), arno.krenzinger@ufrgs.br (A. Krenzinger), faustino.chenlo@ciemat.es (F. Chenlo Romero).

http://dx.doi.org/10.1016/j.rser.2014.03.047
1364-0321/

different configurations. However, to perform a simulation that return reliable data is necessary to use software that incorporates mathematical models capable of describing accurately the behavior of the components of a photovoltaic system. These models must be experimentally validated and obtained from specific tests.

Grid connected photovoltaic system does not use batteries to energy storage and the electricity output varies throughout the day. This means that there is little influence of prior history to determine what happens in the time interval being analyzed. At intervals of about 1 min, the memory of the past behavior is restricted to the thermal effects considered in modules and inverters. Except for these, it can be said that the electrical energy injected on the grid is dependent on only a set of variables and parameters defined instantaneously. In fact it would be enough to establish the temperature values for modules and inverters and the solar irradiance as parameters for a set of equations for the entire simulation.

## 2. The inverter

The inverter converts DC power from the PV system on AC power that will be injected into the grid. The development of electronic technology has allowed considerable increase in the conversion efficiency, together with increased reliability and reduced costs.

\Historically, low power photovoltaic systems use single-phase inverters. In grid connected applications, the single-phase inverters produce an imbalance between the phases by injecting current into only one phase of the grid. Due to stability reasons, it is possible to connect a maximum power of 4.6 kW, with 10% of tolerance, at one stage to avoid a greater asymmetry between the phases of the grid [3]. For power greater than 5 kW three single-phase inverters are needed to ensure a balanced distribution between the three phases [3]. The inverters used in grid connected photovoltaic systems use different circuits for energy conversion and there are a number of options of transformer configuration. There are commercial inverters with high or low frequency transformers and even transformerless inverters. Each topology has its own characteristics, resulting in advantages and disadvantages [4–9]. The inverters used in grid-connected applications embed maximum power point tracker, anti-islanding operation, high conversion efficiency, automatic synchronization with the grid and they have low level of harmonics distortion and power factor close to unity [10–12]. The performance of the inverters connected to the grid depends largely on the control strategy applied [13,14].

### 2.1. DC to AC conversion efficiency

The DC to AC conversion efficiency of the inverter (Eq. (1)) is set as the ratio between the output power of the inverter and the input power of the inverter [15].

$$\eta_{inv} = \frac{E_{AC}}{E_{DC}} = \frac{\int P_{AC}\,dt}{\int P_{DC}\,dt} \quad (1)$$

where $E_{AC}$ is the output electrical energy; $E_{DC}$ is the input electrical energy, $P_{AC}$ is the output power and $P_{DC}$ is the input power.

The European efficiency and Californian Efficiency are defined based on weighting of inverter efficiency for different powers Eqs. (2) and (3).

$$\eta_{EU} = (0.03\eta_{5\%}) + (0,06\eta_{10\%}) + (0.13\eta_{20\%}) + (0.1\eta_{30\%}) + (0.48\eta_{50\%}) + (0.2\eta_{100\%}) \quad (2)$$

$$\eta_{CAL} = (0.04\eta_{10\%}) + (0.05\eta_{20\%}) + (0.12\eta_{30\%}) + (0.21\eta_{50\%}) + (0.53\eta_{75\%}) + (0.05\eta_{100\%}) \quad (3)$$

where $\eta_{5\%}$, $\eta_{10\%}$, $\eta_{20\%}$, $\eta_{30\%}$, $\eta_{50\%}$, $\eta_{75\%}$ and $\eta_{100\%}$ are the values of conversion efficiency, respectively 5%, 10%, 20%. 30%, 50%, 75% and 100% rated power of the inverter.

The DC to AC conversion efficiency is strongly dependent on the relative power. The DC voltage also affects the conversion efficiency, although this dependence is often overlooked in the simplest mathematical models that represent the electrical behavior of the inverter. The efficiency also has temperature dependence, although it is advisable not to disregard this dependence increase the complexity of the mathematical model. Tests conducted at Sandia National Laboratories show that the DC to AC efficiency has negligible dependence with the temperature [16]. Mathematical models of inverters, usually determine the conversion efficiency using different parameters associated with thermal and electrical losses resulting from the conversion process.

A model found in the literature suggests that the efficiency can be obtained from the interpolation of experimental data [17]. The efficiency for a given power is determined Eq. (4) by linear interpolation within a given power range, where the efficiencies of the inverter correspondent to the lower limit and to the upper limit of power are known.

$$\eta_{inv} = \eta_{inf} + \frac{(P_{AC} - P_{inf})(\eta_{sup} - \eta_{inf})}{(P_{sup} - P_{inf})} \quad (4)$$

where $P_{inf}$ is the lower limit of power; $P_{sup}$ is the upper limit of power; $\eta_{inf}$ is the inverter efficiency in the lower limit of power and $\eta_{sup}$ is the inverter efficiency in the upper limit of power.

Another proposed model for the efficiency Eq. (5) is based on the equivalent circuit consisting of an ideal inverter, a series resistance that represents the ohmic losses and a parallel resistor which represent the self-consumption [18].

$$\eta_{inv} = \frac{2R_S P_{AC}}{V_{DC}^2} \frac{1}{1 - \sqrt{1 - 4\left(R_S/V_{DC}^2\right)\left(P_{AC} + \left(V_{AC}^2/R_P\right)\right)}} \quad (5)$$

where $V_{DC}$ is the input voltage of the inverter; $V_{AC}$ is the output voltage of the inverter; $R_S$ is the series resistance; $R_P$ is the parallel resistance.

The model can be extended also to reactive loads Eq. (6) considering the apparent power and including a factor that has a value close to unity except for very low power factors and also represents additional losses due to high internal reactive currents.

$$\eta_{inv} = \frac{2R_S S}{V_{DC}^2} \frac{a}{1 - \sqrt{1 - 4\left(R_S/V_{DC}^2\right)\left(P_{AC} + \left(V_{AC}^2/R_P\right)\right)}} \quad (6)$$

Another model found in the literature is a simple mathematical model where the lost converting energy is represented by a polynomial [19]. The model coefficients are associated with different sources of electrical losses of the inverters Eq. (7).

$$\eta_{inv} = \frac{(P_{AC}/P_{NOM})}{(P_{AC}/P_{NOM}) + (K_0 + K_1(P_{AC}/P_{NOM}) + K_2(P_{AC}/P_{NOM})^2)} \quad (7)$$

where $K_0$, $K_1$ and $K_2$ are mathematical coefficients and $P_{NOM}$ is the nominal power of the inverter.

A mathematical model to describe the performance of inverters used in grid connected photovoltaic systems was empirically developed. From the relationship between the $P_{DC}$ and $P_{AC}$ the model coefficients are determined Eqs. (8) and (9) [16].

$$P_{AC} = \left(\frac{P_{ACO}}{(A-B)} - C(A-B)\right)(P_{DC} - B) + C(P_{DC} - B)^2 \quad (8)$$

$$A = P_{DCO}(1 + C_1(V_{DC} - V_{DCO})), \quad B = P_{SO}(1 + C_2(V_{DC} - V_{DCO})), \quad C = C_0(1 + C_3(V_{DC} - V_{DCO})) \quad (9)$$

where $P_{AC}$ is the output power of the inverter; $P_{ACO}$ is the output maximum power of the inverter; $P_{DC}$ is the input power of the