Chapter 9
Implementation and Validation of Energy Conversion Efficiency Inverter Models for Small PV Systems in the North of Brazil

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Abstract The increasing amount of distributed photovoltaic (PV) system components into distribution networks involves the development of accurate simulation models that take into account an increasing number of factors that influence the output power from the distributed generation systems. The modeling of PV system components in power systems and the relative control architecture is an important part of the introduction of a relevant quantity of renewable energy to the future development of the smart grid. Therefore, it is essential to have proper validated models to help operators perform improved studies and be more confident with the results. We present two energy conversion efficiency inverter models developed for two small PV systems using the Jantsch inverter models (Jantsch, Schmidt, Schmid, Results of the concerted actions on power conditioning and control. XI European Photovoltaic Solar Energy Conference, Swiss, 1992) and Sandia inverter model (King, Gonzalez, Galbraith, Boyson,Performance model for grid-connected photovoltaic inverters, Sandia National Laboratory Report, New México, 2007).

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The component models were implemented in MATLAB software and the simulation results were compared, firstly, with the datasheet values of the inverter Xantrex GT2.8-NA-240/208 UL-05 model and then with the microinverter Enphase® Energy (M215) model. To confirm the strong dependency on ambient conditions and to validate the simulation models, operation data from two small PV systems using the Xantrex and Enphase Energy inverters located in the north of Brazil were used and statistical analysis and comparison of the results was performed.

Keywords Conversion efficiency inverter models · System performance validation · Computational simulation · Small grid-connected PV systems

9.1 Introduction

The evaluation of energy conversion efficiency and hence the operation of inverters for photovoltaic (PV) systems connected to the grid are based on electrical parameters (voltage input and output, DC and AC power circuits, etc.) and thermal equipment. Several mathematical models of energy conversion efficiency inverters for such systems have been developed over time [1–4]. For sizing PV systems, designers need a reliable mathematical model and simple application that performs computer simulations and consequently generates estimates of energy production of PV systems with a lower margin of uncertainty in order to provide better financial return and investment in the project.

Here, we studied two energy conversion efficiency inverter mathematical models for grid-connected PV systems proposed by [1, 2]. They were chosen because they are simple to operate and because each one is based on data from the manufacturer's inverter datasheets and can also use operational data (from the field) of inverters that are coupled to small PV systems in real operation conditions. Each one was implement in a mathematical computational tool and validated, under different climatic conditions, by operating data from the Xantrex GT2.8-NA-240/280 UL-05 inverter and the Enphase® M215-60-2LL-S22-IG microinverter and data from the manufacturer's datasheets [5, 6]. In the following sections we present the cited models, their development, validation and results analysis using statistical indicators.

9.2 Methodology

The models proposed by [1, 2] were chosen and implemented using MATLAB® software R2013a. Each one was validated using datasheets from the inverter manufacturers [5, 6], and field data from two small PV systems operating under different environmental conditions. The Xantrex model (rated at 2.8 kW) is coupled to a grid-connected PV system with 3.36 kWp installed power, with m-Si modules Kyocera

KC 120. The Enphase model with 215 W nominal power is coupled to a 245 Wp PV module (m-Si Aleo S19G245) in a bus interconnected to a 220 V AC grid. Both systems were located in the test area of the Group of Studies and Development of Alternatives Energy (GEDAE) at the Federal University of Pará (UFPA) in Belém city in the north of Brazil. A detailed description of these small PV systems, their instrumentation, and monitoring and data acquisition are described in [7, 8]. The data generated by the inverters were first treated and then applied to the models. A comparison of datasheets and field data was carried out using two figures of merit commonly used in statistical literature [9, 10]—MBE[1] and RMSE[2] errors and a parallel of the models was performed. Equations (9.1) and (9.2) show the calculations of average errors where 'K' is a general variable and 'n' is the number of datasets used.

$$RMSE = \left(\frac{1}{n} * \sum_{i=1}^{n} \left(k_{\text{calculated}} - k_{\text{measured}} \right)^2 \right)^{\frac{1}{2}} \quad (9.1)$$

$$MBE = \frac{1}{n} * \sum_{i=1}^{n} (k_{\text{calculated}} - k_{\text{measured}}) \quad (9.2)$$

9.3 Energy Conversion Efficiency Inverter Mathematical Models for Grid-Connected PV Systems

9.3.1 Jantsch Model

The Jantsch model, developed by [1] proposes the calculation of the losses of the inverter depending on their power output, not taking into account other possible variations that may occur. The model considers the losses as a second-degree function and seeks to connect the terms of each order to the actual losses in the inverters. Eq. (9.3) shows total losses.

$$P_{\text{losses}} = k_0 + k_1 * P_{\text{output}} + k_2 * P_{\text{output}}^2 \quad (9.3)$$

The input power and efficiency are defined as in Eqs. (9.4) and (9.5).

$$P_{\text{input}} = P_{\text{output}} + P_{\text{losses}} = P_{\text{output}} + k_0 + k_1 * P_{\text{output}} + k_2 * P_{\text{output}}^2 \quad (9.4)$$

[1] Mean bias error (MBE) is a systematic error and is the trend of whether the data is overestimated or underestimated.

[2] Root mean square error (RMSE) indicates an average absolute error; the lower the RMSE values, the more accurate the estimate of the model.

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} = \frac{P_{\text{output}}}{P_{\text{output}} + k_0 + k_1 * P_{\text{output}} + k_2 * P_{\text{output}}^2} \tag{9.5}$$

Having knowledge of the parameters k_0, k_1 and $k_{2,}$ can set losses throughout the range of operation of the inverter, and the energy conversion efficiency. These characteristic parameters are defined by Eqs. (9.6), (9.7) and (9.8).

$$k_0 = \frac{1}{9} * \frac{1}{\eta_{\text{inv}} 1} - \frac{1}{4} * \frac{1}{\eta_{\text{inv}} 0.5} + \frac{5}{36} * \frac{1}{\eta_{\text{inv}} 0.1} \tag{9.6}$$

$$k_1 = \frac{-4}{93} * \frac{1}{\eta_{\text{inv}} 1} + \frac{33}{12} * \frac{1}{\eta_{\text{inv}} 0.5} - \frac{5}{12} * \frac{1}{\eta_{\text{inv}} 0.1} - 1 \tag{9.7}$$

$$k_2 = \frac{20}{9} * \frac{1}{\eta_{\text{inv}} 1} - \frac{5}{2} * \frac{1}{\eta_{\text{inv}} 0.5} + \frac{5}{18} * \frac{1}{\eta_{\text{inv}} 0.1} \tag{9.8}$$

where $\eta_{\text{inv}}1$, $\eta_{\text{inv}}0.5$ and $\eta_{\text{inv}}0.1$ refer to the instant efficiencies at 100, 50 and 10% of rated output power, respectively. K_0 is the loss of self-consumption, without depending on power output. K_1 refers to the linear losses in power output (e.g. voltage drops in semiconductor devices, diodes and switches, IGBT). Finally, K_2 is the quadratic loss with output power, for example, the ohmic losses.

9.3.2 Sandia Model

The mathematical model of the energy conversion efficiency for PV inverters proposed by [2], also called the Sandia/King model, is an empirical model which has good accuracy in results and good versatility, having been successfully applied to large and small PV systems. The model consists of an expression that relates AC power inverter output as a function of input power and DC bus voltage; these being the two variables needed to estimate the behavior of the conversion efficiency for an inverter. The Sandia model is described by the power AC expression, Eq. (9.9), which is complemented by Eqs. (9.10), (9.11), (9.12).

$$P_{\text{ac}} = \left\{ \left(\frac{P_{\text{aco}}}{A - B} \right) - C * (A - B) \right\} * (P_{\text{dc}} - B) + C * (P_{\text{dc}} - B)^2 \tag{9.9}$$

$$A = P_{\text{dco}} * \{1 + C_1 * (V_{\text{dc}} - V_{\text{dco}})\} \tag{9.10}$$

$$B = P_{\text{so}} * \{1 + C_2 * (V_{\text{dc}} - V_{\text{dco}})\} \tag{9.11}$$

$$C = C_0 * \{1 + C_3 * (V_{\text{dc}} - V_{\text{dco}})\} \tag{9.12}$$

where P_{ac} is the power output of the inverter, P_{dc} is the input power of the inverter, P_{aco} is rated output; P_{dco} is the input power to the inverter-rated power supply output, P_{so} is own consumption or minimum power for start-up of the inverter, V_{dco} is nominal voltage, and V_{dc} is input voltage.

9.4 Validation of Jantsch and Sandia Models

9.4.1 *Analysis of Results for the Xantrex GT2.8-NA-240/208 UL-05 Inverter*

Table 9.1 shows the performance of the Jantsch and Sandia models by comparing the results of MBE and RMSE using data from the manufacturer's datasheet and field data measurements.

According to Table 9.1, for output power and also efficiency (through RMSE% error), the Jantsch model showed better results compared to the Sandia model, when used datasheet data. However, the ($\Delta_{datasheet}$) difference between the numerical results for the RMSE% error is sparingly small between models, for example, 0.05 % (for output power) and 0.07 % (for efficiency). Compared to field data, the Sandia model showed better results (for the output power) and the Δ_{field} difference is equal to 0.02 %; however, for efficiency, the Jantsch model was slightly better but the Δ_{field} difference is equal to 0.03 %, which is still very low. Therefore, both models showed good quality outcomes, mean errors, and are very similar. Therefore, both models represented the inverter manufacturer Xantrex model GT 2.8 kW well.

Regarding the indicator MBE% error, for output power in Table 9.1, the Sandia model tended to underestimate (−0.17 %) but the Jantsch model tended to overestimate (0.11 %) the datasheet data ($\Delta_{datasheet}$) showing a value equal to 0.28 %, i.e., a small variation in the end result. For the field data, both models underestimated, but datasheet data ($\Delta_{datasheet}$) showed a very low result (0.03 %) between the models. Regarding MBE% for the efficiency using datasheet data, the Sandia model

Table 9.1 Results obtained for the Jantsch and Sandia models from field data and datasheet data

Sandia and Jantsch models (Xantrex GT2.8)		Data			
		Datasheet (%)	$\Delta_{datasheet}$ (%)	Field (%)	Δfield (%)
Output power	$RMSE\%_{Sandia}$	0.22	0.05	0.10	0.02
	$RMSE\%_{jantsch}$	0.17		0.12	
	$MBE\%_{Sandia}$	−0.17	0.28	−0.06	0.03
	$MBE\%_{Jantsch}$	0.11		−0.09	
Efficiency	$RMSE\%_{Sandia}$	1.15	0.07	1.07	0.03
	$RMSE\%j_{antsch}$	1.12		1.04	
	$MBE\%_{Sandia}$	−0.70	0.85	−0.40	
	$MBE\%_{Jantsch}$	0.15		−0.45	0.05

had a tendency to underestimate (−0.70 %) as opposed to the Jantsch model which overestimated their perspective (0.15 %); the ($\Delta_{datasheet}$) between models was 0.85 %. Regarding efficiency using field data, again both models tended to underestimate but ($\Delta_{datasheet}$) between models was very low; therefore, the results achieved were almost similar between the two models in this regard.

Finally, Table 9.1 shows good results (RMSE% and MBE% errors) for efficiency and output power, good equivalence and small variations in values (as mentioned above), showing the high quality of the Sandia and Jantsch models for representing a model of energy conversion efficiency to the Xantrex GT 2.8 kW inverter. Figure 9.1 shows the efficiency curves for the Jantsch model for the manufacturer's datasheet (black curve), for field measurements (red curve) and the curve of the inverter under real operation conditions (green) and Fig. 9.2 shows the efficiency curves for the Sandia models for the Xantrex GT 2.8 kW inverter. The red curve is from the datasheet, the black curve is from field measurements and the green curve is the actual curve of the inverter in real operation conditions.

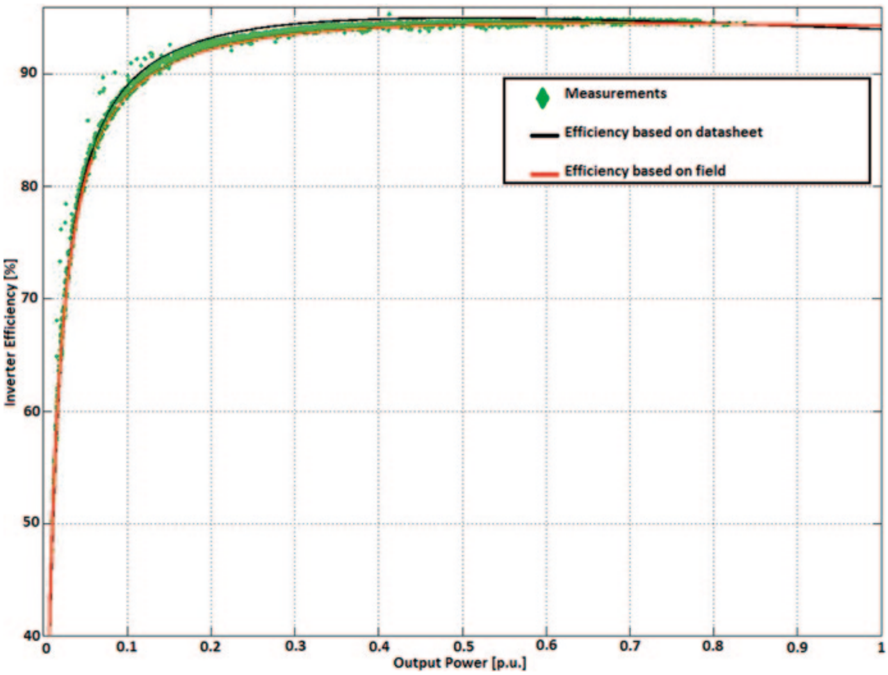

Fig. 9.1 Efficiency curves of the Jantsch model for the Xantrex GT 2.8 kW inverter using datasheet data and field data

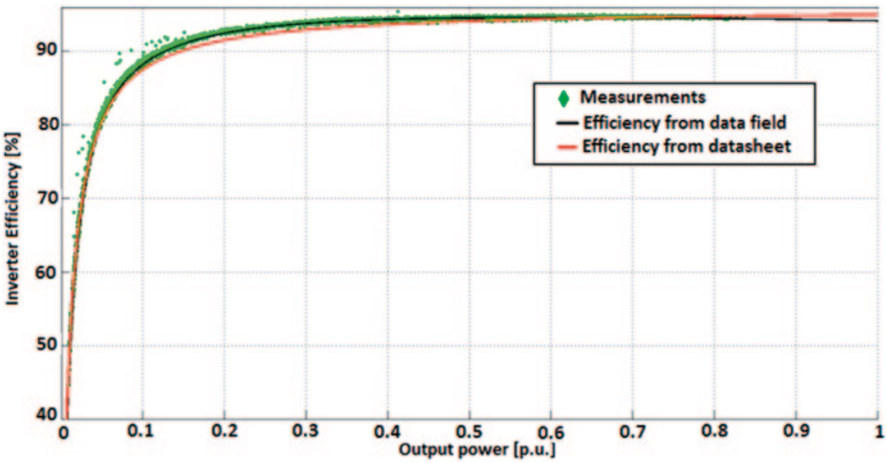

Fig. 9.2 Efficiency curves of the Sandia model for the Xantrex GT 2.8 kW inverter using datasheet data and field data

9.4.2 Analysis of Results for the Enphase Energy 215-60-2LL-IG Microinverter

Table 9.2 shows the performance of the Jantsch and Sandia models compared with the results of MBE% and RMSE% errors using data from the manufacturer's datasheet and from field measurements.

According to Table 9.2, for the output power and also efficiency (through RMSE% error), the Jantsch model showed worse results in comparison with the Sandia model, when using datasheet data. However, the ($\Delta_{datasheet}$) difference between the numerical results for the RMSE% error is very small between models, for example, 3 % (for output power). For efficiency, when using datasheet data, the

Table 9.2 Results for the Jantsch and Sandia models from field measurements and datasheet data

Sandia and Jantsch models (Enphase Energy 215 W)		Data			
		Datasheet (%)	$\Delta_{datasheet}$ (%)	Field (%)	Δ_{field} (%)
Output power	$RMSE\%_{Sandia}$	1.26	3	1.16	0.25
	$RMSE\%_{Jantsch}$	4.26		0.91	
	$MBE\%_{Sandia}$	−0.17	3.81	−0.06	0.33
	$MBE\%_{Jantsch}$	3.98		0.27	
Efficiency	$RMSE\%_{Sandia}$	13.56	8.44	4.34	0.04
	$RMSE\%_{Jantsch}$	22		4.30	
	$MBE\%_{Sandia}$	0.35	14.85	0.57	
	$MBE\%_{Jantsch}$	15.20		1.37	0.8

RMSE% error was quite high for both models with values > 10 %. Compared with field data, the Sandia model showed worse results (for the output power) and the difference (Δ_{field})with a value equal to 0.25 %; however, for efficiency, the Jantsch model was slightly better with a (Δ_{field}) difference equal to 0.04 %, which was very low. Therefore, for both models, the RMSE% error output power showed good quality for datasheet data and field data with small variations; however, for efficiency, the RMSE% error for the Sandia and Jantsch models using datasheet data was high, showing poor quality for both models. On the other hand, for efficiency, the RMSE% error was very similar (4.30 %) and therefore both models represented the microinverter Enphase Energy 215 W for field data well.

Regarding the indicator MBE% error to the power output in Table 9.2, the Sandia model tended to underestimate (−0.17 %) but the Jantsch model tended to overestimate (3.98 %) using datasheet data with $\Delta_{datasheet}$ equal to 3.81 %. The same happened for field data for both models. The Sandia model tended to underestimate (−0.06 %) while the Jantsch model tended to overestimate (0.27 %) with Δ_{field} equal to 0.33 %. Regarding MBE% error for efficiency with datasheet data, both models had a tendency to overestimate (0.35 % for Sandia and 15.20 % for Jantsch) with $\Delta_{datasheet}$ equal to 14.85 %. Regarding efficiency with field data, again both models tended to overestimate but with small values (0.57 % for Sandia and 1.37 % for Jantsch) with Δ_{field} equal to 0.8 %, showing that the difference between the models is very low; therefore, the result achieved were almost similar between the two models in this regard.

Finally, Table 9.2 shows good results; the RMSE% and MBE% errors for efficiency and output power showed good equivalence and small variations in their values (as mentioned above), showing the high quality of the Sandia and Jantsch models for representing a model of energy conversion efficiency to the Enphase Energy 215 W inverter for field measurements. Figure 9.3 shows the efficiency curves for the Jantsch model for the manufacturer's datasheet (green curve), for field measurements (red curve) and the curve of the inverter for real operation conditions (dots blue). Fig. 9.4 shows the efficiency curves for the Sandia model for the Enphase Energy 215 W inverter. The red curve is from datasheet data, the black curve is from field measurements and the green curve (dots) is the actual curve of the inverter in real operation conditions.

9.5 Conclusion

Regarding the validation of the Jantsch and Sandia models using MBE% and RMSE% errors, both showed good results on average errors, good equivalence between models and small variations between their values (as shown in Sect. 4.1). This confirmed the high quality of the Sandia and Jantsch models for representing the energy conversion efficiency for the Xantrex model GT 2.8 inverter.

For the Enphase Energy model M215-60-2LL-S22-IG microinverter, the validation of the Jantsch and Sandia models was good for power output and efficiency

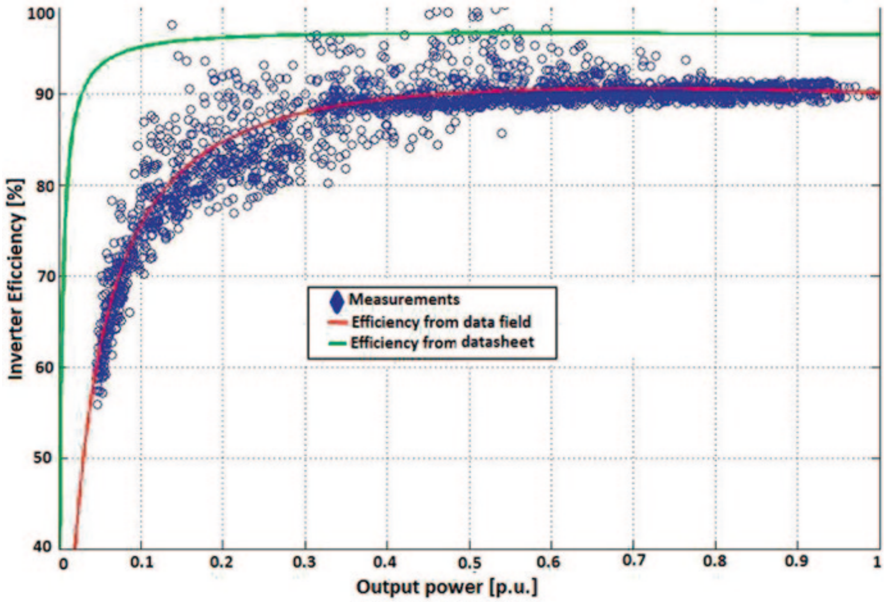

Fig. 9.3 Efficiency curves of the Jantsch model for the Enphase Energy model M215 microconverter using datasheet data and field data

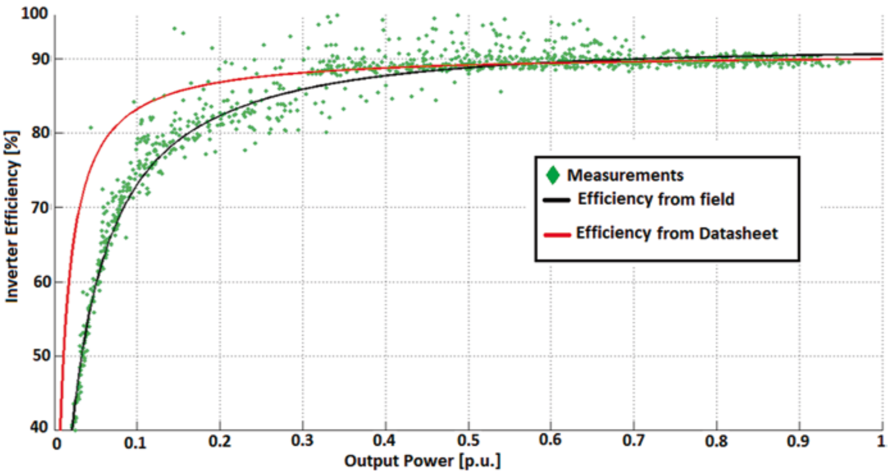

Fig. 9.4 Efficiency curves of the Sandia model for the Enphase Energy model M215 microinverter using datasheet data and field data

for data from field measurements with slight variations as shown in Table 9.2. This demonstrates the quality of both models for representing the energy conversion efficiency for the inverter. On the other hand, for datasheet data, the Sandia and Jantsch models presented very high values for RMSE% errors for efficiency. The explanation for this refers to datasheet data from the manufacturer that provides values for the efficiency curve beginning at 10 % of rated output power disregarding the values below this loading; therefore, increasing the average error and the quality of the models. Note, for MBE% errors, the Sandia model results were better than the Jantsch model. Finally, the Sandia and Jantsch mathematical models are a good and reliable for representing the energy conversion efficiency for an inverter for computer simulations and consequently to generate estimates of energy production of PV systems under different climatic conditions.

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