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Modeling Efficiency of Inverters with Multiple Inputs

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Abstract—**Inverters convert DC power to AC power that can be injected into the grid. Many inverters offer multiple, independent maximum power point trackers (MPPTs) to accommodate photovoltaic arrays with different orientations or capacities. No validated model for overall DC-to-AC power conversion efficiency is available for such inverters. Herein, we propose a mathematical model that describes the efficiency of a multi-MPPT inverter and present validation using a commercial inverter with six MPPT inputs.**

Keywords—inverter, modeling, efficiency, power electronics

I. Introduction

Modeling photovoltaic (PV) system performance requires a model for the DC-to-AC power conversion efficiency of the system's inverters. Available inverter models [1], [2], [3] describe inverter conversion efficiency as a function of input DC power and DC voltage. These models were developed and validated for inverters with a single maximum power point tracker input. Each model employs parameters fitted to observed conversion efficiency curves to predict conversion efficiency at any condition.

Many inverters now offer multiple, independent maximum power point trackers (MPPTs). Multiple MPPTs allow an inverter to maximize energy conversion from PV arrays with different orientation, capacity and shading, and thus with DC power and DC voltage varying among the arrays. To our knowledge, no model specific to multi-MPPT inverters has been published and validated, although some PV simulation software (e.g. [5]) include models for PV systems with multiple arrays.

Here, we extend the single-input model in [1] to a form applicable to multi-input inverters. The procedure is not specific to the model form in [1] and thus may also indicate how the models in [2] and [3] could also be extended. A python implementation of the resulting model is available in pvlib-python [4] as the `pvlib.inverter.sandia_multi` function.

Bower et al. [5] published a procedure for measuring inverter efficiency over a range of test conditions. This procedure produces data that can be used to fit the inverter model in [1]. Test results for many inverters are recorded in the California Energy Commission (CEC) Equipment List[1]. The test procedure is also being applied to multi-input inverters, but in a limited manner: inverter efficiency measurements are made with equal DC voltage and DC power applied to each input (according to private communications).

For fitting and validation of the extended model, inverter AC power is measured for a commercial device with six MPPT inputs, with the DC voltage and DC power at each input varied over a matrix of test conditions. We calibrate the extended inverter model using only this "equal input" data and show that the model accurately predicts inverter conversion efficiency when unequal DC voltage and/or DC power are supplied on different inputs.

We compare our model with the multi-input inverter model implemented in the System Advisor Model (SAM) [6]. Our new model predicts conversion efficiency without a bias toward underprediction at low input power that is observed in the output of SAM.

II. Derivation of the Multi-Input Inverter Model

Available PV inverter models (e.g., [1]) are of the form:

$$P_{AC} = min\{f(P_{DC}, V_{DC}), P_{AC,max}\} \quad (1)$$

where P_{DC} is the total input DC power, V_{DC} is input DC voltage (assumed to be the same at each DC input) and $P_{AC,max}$ is the PV inverter's AC power limit. The function form f accounts for the dependence of conversion efficiency on input power and voltage, as well as factors such as input or output power limiting, minimum start-up power, self-consumption by the inverter, and voltage limits.

An inverter with several MPPTs comprises two functional stages in sequence:

1. A DC-DC converter on each input, which holds the connected array at the array's MPP, and converts the input DC voltage to a DC bus at a common DC voltage.
2. A DC-AC inverter stage which produces AC power from the DC power on the DC bus.

Fig. 1 illustrates a block diagram of a PV inverter with multiple MPPTs and assigning variables to DC voltage and power on each input and on the bus. Not every input needs to be connected to a PV array.

[1] https://www.energy.ca.gov/programs-and-topics/programs/solar-equipment-lists

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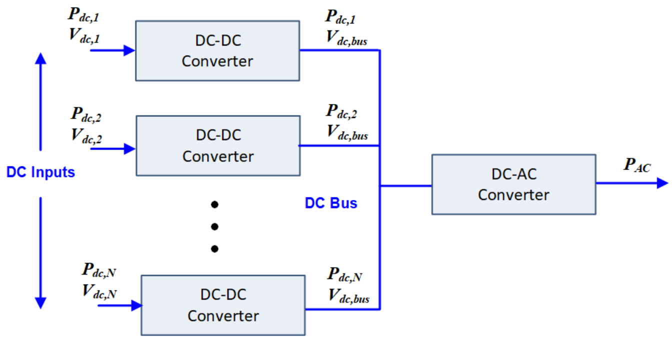

Fig. 1. Block Diagram of a Multi-Channel PV Inverter.

We derive an extension of the model represented by Eq. 1 to multi-MPPT PV inverters that can be calibrated using only the "equal input" data collected according to [6]. Denote the AC power that results from DC input to one MPPT as

$$P_{AC,i} = g_i\left(P_{dc,i}, V_{dc,i}\right) \tag{2}$$

where i indexes the MPPT inputs. Assume that all DC-DC converters are equally efficient, i.e., the function g_i is the same for every MPPT input and we can drop the subscript from g. Assume that each DC-DC converter acts independently, i.e., $P_{AC,i}$ is independent of $P_{AC,j}$ for $i \neq j$. Then the sum over all MPPT inputs results in the total output AC power:

$$P_{AC} = f(P_{DC}, V_{DC}) = \sum_{i=1}^{N} P_{ac,i} = \sum_{i=1}^{N} g\left(P_{dc,i}, V_{dc,i}\right) \tag{3}$$

When multi-input inverters are tested using the "equal power" method, then at each test point (P_{DC}, V_{DC}) the conditions for each MPPT input are the same: $V_{dc,1} = V_{dc,2} = \cdots V_{dc,N} = V_{DC}$ and $P_{dc,1} = P_{dc,2} = \cdots P_{dc,N} = P_{dc} = \frac{1}{N} P_{DC}$. In these conditions $f(P_{DC}, V_{DC})$ is the single-input model, i.e., [1]. It follows that:

$$\begin{aligned} f(P_{DC}, V_{DC}) &= \sum_{i=1}^{N} g\left(P_{dc,i}, V_{dc,i}\right) \\ &= N \times g\left(\frac{1}{N} P_{dc,i}, V_{dc,i}\right) \end{aligned} \tag{4}$$

Applying the change of variables $P_{dc} = \frac{P_{DC}}{N}$ yields:

$$g(P_{dc}, V_{DC}) = \frac{1}{N} f(P_{DC}, V_{DC}) \tag{5}$$

We take Eq. 5 to define the form of the function g, i.e., congruent to the function f evaluated at the total DC power P_{DC} but scaled in amplitude. We generalize from Eq. 5 to define the function g at any set of conditions $P_{dc,i}, V_{dc,i}$ to be:

$$g\left(P_{dc,i}, V_{dc,i}\right) = \frac{P_{dc,i}}{P_{DC}} f\left(P_{DC}, V_{dc,i}\right) \tag{6}$$

With this definition of g, the extended model for the AC output of an inverter with multiple MPPTs is a weighted sum of the output of the single-input inverter model, applied at each MPPT input to total DC power and the DC voltage at the MPPT input:

$$P_{AC} = min\left\{\sum_{i=1}^{N} \frac{P_{dc,i}}{P_{DC}} f\left(P_{DC}, V_{dc,i}\right), P_{AC,max}\right\} \tag{7}$$

$$P_{DC} = \sum_{i=1}^{N} P_{dc,i} \tag{8}$$

III. Measurements

AC power is measured for a SMA Tripower Core1 inverter with a power rating of 33kVA, an operating voltage of 480 V_{AC} and six independent MPPT inputs. Tests were conducted using the open-source System Validation Platform (SVP) and the power hardware-in-the-loop architecture in Fig. 2. Scaled analog voltage signals were sent to a 180 kVA, 480 VAC AMETEK AC power amplifier to provide an AC voltage signal to the PV inverter. DC power for each input to the inverter was provided by a 200 kW, 1000 VDC AMETEK TerraSAS programmable PV simulator. The current and voltage responses from the PV inverter were recorded using MATLAB/Simulink.

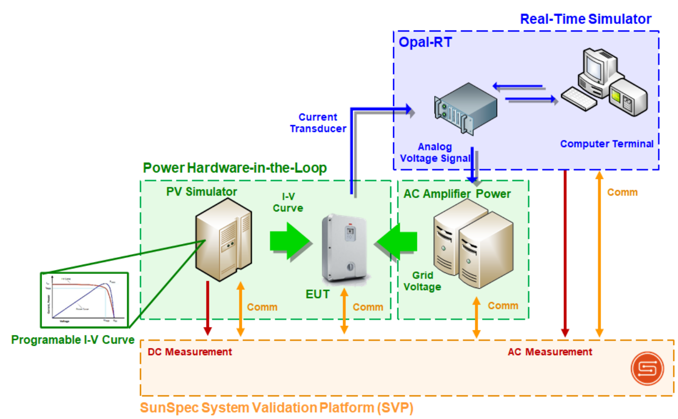

Fig. 2. Testbed for measuring inverter efficiency.

IV. Results

Parameters for the inverter model [1] were determined by applying the '`fit_sandia`' function in pvlib-python [3] to the "equal power and voltage" subset of the test results. The fitted model is used to predict AC power at all test conditions and predicted power is compared to measurements. Fig. 3 illustrates the predicted inverter efficiency (top) and the relative error at each test point (bottom). The results demonstrate that the proposed model is generally unbiased with prediction accuracy between ±0.5%. Variance in inverter efficiency is observed at each level of DC input power and DC voltage. This variance appears to arise from variability in the laboratory measurements or from the dynamics of the inverter's MPPT algorithm. The variance does not correlate with the DC power level on any specific MPPT input (Fig. 4).

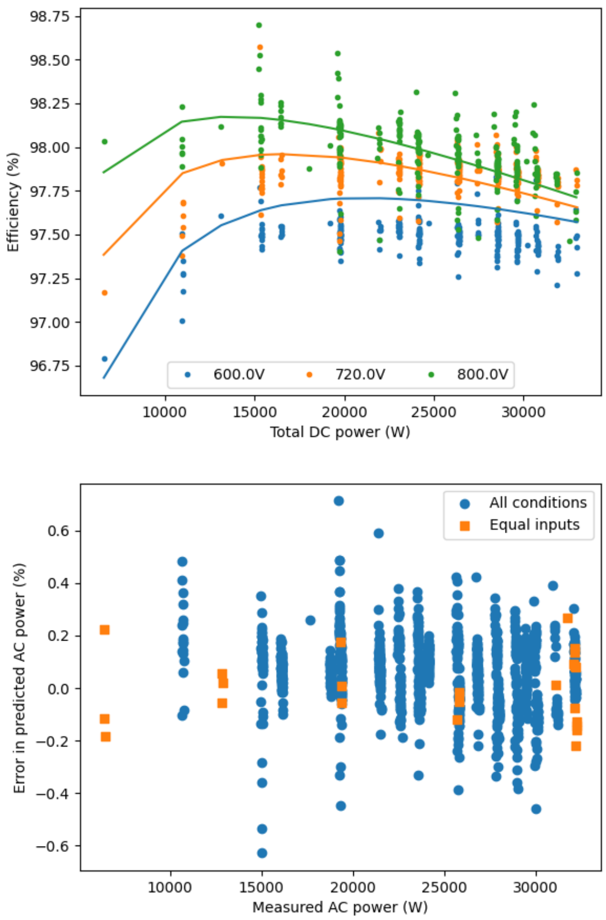

Fig. 3. Measured and predicted efficiency (top), and error in predicted AC power (bottom).

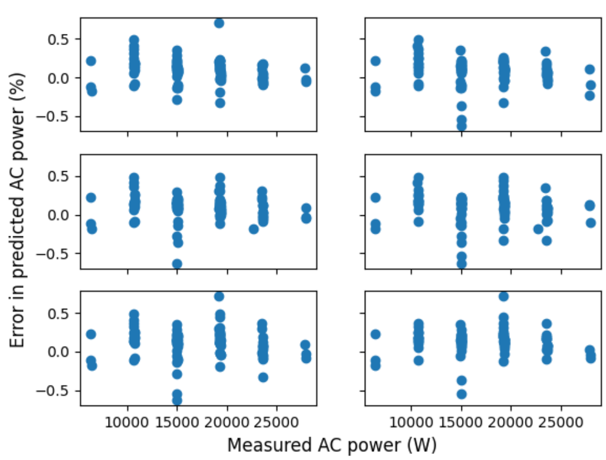

Fig. 4. Error in predicted AC power separated by input.

V. Comparison with the SAM Inverter Model

The multi-inverter model implemented in SAM version 2021.12.02 is shown in Eq. 9. The function f represents the model described in [1] fit to data measured with equal power and voltage on each input. This model omits the weighting of AC power produced from the DC power at each MPPT input and applies the function f to the DC power on each input $P_{dc,i}$, rather than to the total DC power P_{DC}. Consequently, the model uses only on the lower range of the curve relating input DC power to efficiency (Fig. 3 (top)) as consequently, underestimates AC power at all power levels (Fig. 5). The SAM development team plans to update the multiple-input inverter model to be consistent with the model described in Eq. 7 and Eq. 8 (private communication).

$$P_{AC} = min\left\{\sum_{i=1}^{N} f\left(P_{dc,i}, V_{dc,i}\right), P_{AC,max}\right\} \quad (9)$$

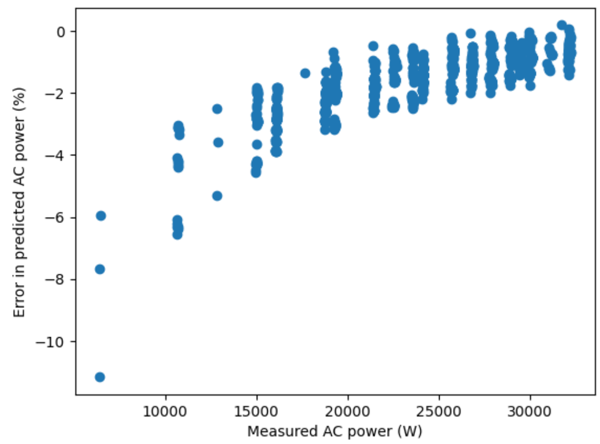

Fig. 5. Error in predicted AC power using the SAM model.

Acknowledgment

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