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Sandia Inverter Performance Test Protocol Efficiency Weighting Alternatives

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***Abstract*—The Sandia Inverter Performance Test Protocol defined two possible weighted-average efficiency values for use in comparing inverter performance, of which one definition was selected by the California Energy Commission for use in their Buydown incentive program leading to widespread use in the photovoltaic inverter market. This paper discusses the derivation of the efficiency weights originally proposed, and investigates the potential for defining new weights in light of increased array-to-inverter (DC-to-AC) system rating ratios in modern PV systems.**

***Index Terms*—inverter efficiency, DC-to-AC rating ratio, weighted efficiency.**

I. Introduction

Sandia National Laboratories is sponsoring an effort to finalize the Sandia Inverter Test Protocol. The last draft of this document, published in November 2004[1] specifies testing of inverter efficiency at seven power levels and three DC voltage levels. To reduce complexity for assessing overall inverter efficiency, both “nominal inverter efficiency” and “weighted inverter efficiency” values were defined that combine the individual test results to get overall measures of inverter efficiency. The power levels specified for efficiency testing in the 2004 version of the protocol document were adapted from IEC61683:1999 [2] to include efficiency testing at 75% of rated, and to exclude the 120% level that is not typically feasible with grid-connected inverters.

The California Energy Commission (CEC) commissioned a report [3] that identified a subset of the Sandia tests that would be required for listing equipment on the CEC database of approved equipment for financial incentives in the state of California. One notable recommendation of this document was the elimination of the requirement to test efficiency at 5% of inverter rated power due to difficulty of obtaining accurate results at low power and diminishing returns on test cost. Another significant recommendation was to use the “Weighted Efficiency” as the basis for the inverter contribution to the determination of an incentive amount rather than the Nominal Average Efficiency. This application of the weighted inverter efficiency has given these weighting factors a significant edge for inverter marketing and design purposes.

With 9 years of products having been tested to meet CEC incentive requirements, in 2014 a large number of inverters have publically-reported test results at three DC voltages and six power levels along with corresponding overall “CEC” weighted efficiency (unweighted mean of the weighted average efficiency for each of the three DC voltage levels). Because the weighting values used for computing the CEC efficiency were derived assuming the STC rating of the PV array was the same as the AC output rating of the inverter ($kW_p/kW_{AC} = 1.0$), the CEC efficiency may not be a good overall measure of performance for modern applications which are shifting to higher DC-to-AC rating ratios.

This paper investigates the implications of altering these efficiency weighting ratios by examining the impacts of different climates and larger PV arrays.

II. Original Weights Derivation

The original weighting factor computations used in [1] were derived by J. Newmiller under direction of C. Whitaker in 2003. [4] The key principle of derivation was to estimate the power output profile of a “typical” residential PV array in the state of California and formulate a probability density histogram of energy available within the original 7 power bins defined by the Sandia protocol. Bower and Whitaker were aware of the de-facto standard “Euro Efficiency” weighting factors [5] at the time, but those were considered to emphasize low-power operation too much to be useful in the southwest US.

The Sandia weighting derivation began with the typical weather from the Sacramento TMY2 data set [6]. This weather set was deemed to be intermediate between the hotter Southern California climate and the cooler San Francisco Bay Area coastal weather.

The assumed PV array orientation was the 30° fixed south-facing tilted surface that was used for several PV systems at the PVUSA project in Davis, CA. [7] This slope was selected arbitrarily despite the fact that this orientation is slightly steeper than is typical for residential rooftops in California ($18-26°$ tilt). The Perez irradiance transposition algorithm [8] was used to estimate hourly-average plane-of-array irradiance using the Sacramento TMY2 data.

Module temperature was esimated using a quasi-static heat-balance equation with linearized thermal resistance:

$$T_{mod} = \frac{G_{POA}}{800} \cdot (T_{NOCT} - 20) \cdot (1 - \frac{\eta}{R}) + T_{amb} \qquad (1)$$

where G_{POA} is the plane-of-array irradiance (W/m^2), T_{NOCT} is the Nominal Operating Cell Temperature (NOCT) [9] (assumed to be $47\ °C$), η is the irradiance-to-electrical conversion efficiency (assumed to be 0.1), R is the reflected fraction (assumed to be 0.9), and T_{amb} is the ambient air temperature, assumed to be the dry-bulb air temperature from the TMY2 data set.

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The normalized array power was obtained by dividing the hourly average POA irradiance by 1000 W/m^2 and multiplying that normalized power by a temperature correction factor $(1+\beta_{Pmp}\cdot(T_{mod}-25))$ (where β_{Pmp} is the power temperature coefficient, assumed here to be $-0.5\ \%/^{\circ}C$). By treating this normalized power directly as fraction of inverter rated power, the STC rating of the array was implicitly matched to the AC inverter rating (a DC-to-AC ratio of 1.0).

TABLE I
NORMALIZED POWER BINS FOR EFFICIENCY POWER LEVELS

Power	2004 Bin	2004 Weight	CEC Bin	CEC Weight
5%	[0-0.075]	0.00		
10%	[0.075-0.15]	0.04	[0-0.15]	0.04
20%	(0.15-0.25]	0.05	(0.15-0.25]	0.05
30%	(0.25-0.40]	0.12	(0.25-0.40]	0.12
50%	(0.40-0.625]	0.21	(0.40-0.625]	0.21
75%	(0.625-0.875]	0.53	(0.625-0.875]	0.53
100%	(0.875+)	0.05	(0.875+)	0.05

These normalized power levels were sorted into bins per Table I and summed, and then divided by the sum of all bins to obtain a set of power level weighting factors that sum to 1. The normalized power levels were not capped at 1.0 in the original calculation. The original Sandia protocol document specified that a 5% power level be included to be compatible with the Euro efficiency partition, but the poor accuracy at low power levels and negligible weight given to the 5% power level by the Sacramento environment yielded a negligible magnitude for that weight. This led Brooks and Whitaker to merge the weight of the 5% power level with the 10% power level for the CEC inverter test program. Thus, the large database of inverter efficiency curves compiled to date by the CEC conform to the six-bin column of Table I and the rest of this paper will assume that six bins are used.

The resulting set of weights, rounded to 2 decimal places, were used in the 2004 draft of the Sandia Performance Test Protocol. Note that when rounded directly, the sum of the rounded weights do not necessarily add to exactly 1.0, so some judgment was exercised to adjust the weights at this point. The exact calculations and judgment used for the published weights are lost at this point due to computer storage failures and lack of communication with the late C. Whitaker.

III. IMPACT OF NON-UNITY DC-TO-AC POWER RATING RATIO

The use of a DC-to-AC ratio of 1.00 in the original weighting factors was consistent with the desire of the CEC to avoid supporting photovoltaic arrays that were going to "waste" power in an era when the PV array was the major portion of the system cost. In the current market where the PV array is near half the cost of the power system, the additional energy available by operating the system longer at the maximum value allowed by the electric utility interconnection agreement is becoming more economically attractive even though the array may not be operated at maximum efficiency at all times.

In addition to array size, the impact of locating the array in a northern latitude or a high-desert area is considered. The investigation proceeds in two stages: first, the alternate weighting factors are obtained; and second these weighting factors are applied to inverter test data from the existing list of CEC-approved inverters. Although Bletterie [10] points out that power level is correlated with temperature which in turn affects DC voltage and therefore efficiency, no consideration is made here of inverter efficiency impacts due to voltage variation. Also, for consistency with the original method this effort does not attempt use sub-hourly weather as mentioned by Burger [11].

A. Computing New Weights

The cities selected for this exercise are: Sacramento, California (for reference); Alamosa, Colorado (for high-sun cold weather); and Detroit, Michigan (for lower-sun, snow-belt conditions, though snow impact has not been modeled here). The DC-to-AC power rating ratios selected are 1.00 (for reference), 1.25, 1.50 (to our knowledge the highest yet built), and 1.75 (in anticipation that some proposed projects may exceed 1.50).

The substitution of different TMY2 data sets is straightforward. The alternate DC-to-AC ratios are implemented by multiplying the normalized power levels by the assumed ratio and clipping at 1.00 before binning them.

TABLE II
WEIGHTING FACTORS FOR COMBINATIONS OF CITY AND DC/AC RATIOS

City	DC/AC	10	20	30	50	75	100
SACRAMENTO	1.00	0.04	0.05	0.12	0.22	0.53	0.04
SACRAMENTO	1.25	0.02	0.04	0.07	0.13	0.30	0.44
SACRAMENTO	1.50	0.01	0.03	0.06	0.13	0.19	0.58
SACRAMENTO	1.75	0.02	0.02	0.06	0.10	0.11	0.69
ALAMOSA	1.00	0.01	0.03	0.10	0.21	0.43	0.22
ALAMOSA	1.25	0.01	0.03	0.05	0.14	0.23	0.54
ALAMOSA	1.50	0.01	0.03	0.04	0.11	0.16	0.65
ALAMOSA	1.75	0.00	0.02	0.04	0.08	0.14	0.72
DETROIT	1.00	0.05	0.10	0.14	0.25	0.40	0.06
DETROIT	1.25	0.05	0.06	0.12	0.18	0.26	0.33
DETROIT	1.50	0.04	0.04	0.11	0.15	0.18	0.48
DETROIT	1.75	0.03	0.03	0.09	0.14	0.17	0.54

Table II and Fig. 1 present the results of the described alternate weights calculations. The rounding of multiple values leads to an accumulation of error, which has here been allocated to the lowest power bin in order to minimize the impact of error on the results.

B. Applying New Weights to Existing Inverter Efficiency Data

The described weights were applied to available inverter efficiency data extracted from the PDF files posted at the CEC approved products website [12], and differences from the reference efficiency values were compiled. The existing CEC weighted values are rounded to the nearest 0.5% before being reported, so in this work the re-computed values for Sacramento at a ratio of 1.0 are used as the base values for reviewing impact of changes due to location and loading ratio.

Fig. 2 illustrates the reduction in weighted efficiency that occurs when the weighting factors appropriate for unity (red) or high (blue) DC/AC ratios are applied to inverter efficiency

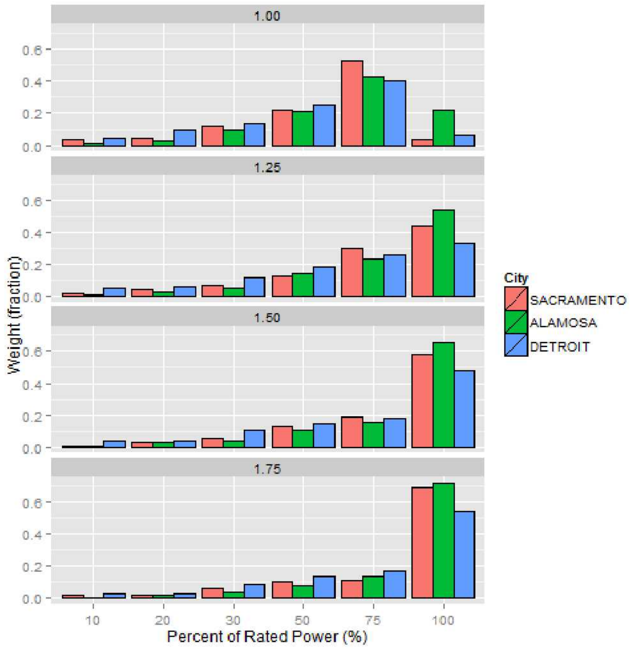

Fig. 1. Weighting Factors for Combinations of City and DC/AC Ratios

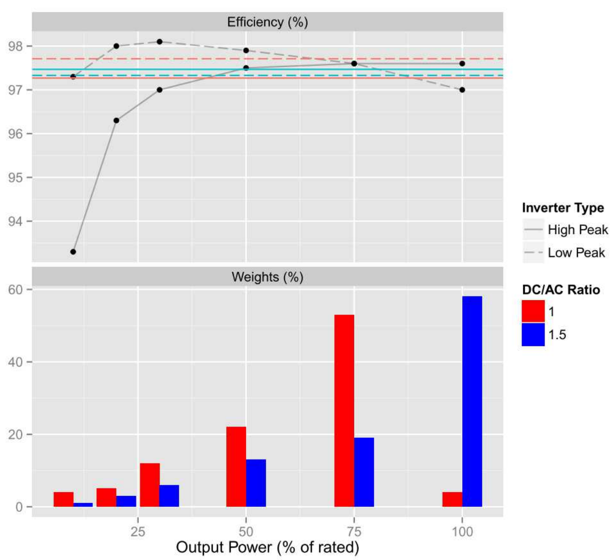

Fig. 2. Sample efficiency curves with weighted efficiencies obtained from two sets of weighting factors

curves with peak efficiency at low and high power levels. The horizontal lines represent the resulting weighted efficiencies. Note that the blue solid line (high power peak efficiency, high DC/AC ratio) is higher than the red solid line (high power peak efficiency, unity DC/AC ratio) indicating that use of these weighting ratios gives credit to the high-power peak efficiency inverter. The fact that the blue solid line is actually higher than the blue dashed line (low power peak efficiency, high DC/AC ratio) illustrates that the natural ranking implied by the CEC

TABLE III
MEAN AND STANDARD DEVIATION OF CHANGES FOR LARGE NEW INVERTERS

City	DC/AC	Mean	StdDev
SACRAMENTO	1.00	0.000	0.000
	1.25	−0.131	0.110
	1.50	−0.163	0.149
	1.75	−0.228	0.163
ALAMOSA	1.00	−0.006	0.083
	1.25	−0.145	0.145
	1.50	−0.194	0.167
	1.75	−0.204	0.198
DETROIT	1.00	−0.042	0.057
	1.25	−0.146	0.050
	1.50	−0.183	0.086
	1.75	−0.185	0.113

efficiency values may not always lead to best performance in-situ.

Having pointed out that the efficiency of heavily-loaded inverters with high CEC efficiency ratings may not be optimal, to be fair we must also point out that while the inverter is operating at maximum output power (clipped) the inverter losses no longer vary significantly with input irradiance (voltage varies slightly with irradiance). The incremental "available" power not delivered at the inverter output terminals is dissipated within the PV array as additional heat by the inverter raising the DC voltage above the array maximum power voltage. From an energy production perspective there is no difference between losing power within the inverter or losing it in the array, so the impact of inverter efficiency on the generated energy is attenuated as time spent clipping increases.

Although operating in power-limited mode may not affect energy generation results, better efficiency within the inverter means reduced thermal dissipation which can have a positive impact on inverter reliability. Conversely, the increased DC voltage associated with power clipping can be expected to have a negative impact on inverter reliability. The significance of these factors may or may not be entirely mitigated by other design decisions, so system integrators should discuss their planned level of DC loading with their inverter suppliers to avoid mis-applying equipment that was designed with low DC loading in mind.

Fig. 3 and Table III present the distributions (for inverters rated larger than 100 kW_{AC} circa 2010 and newer) of change from the base values if the indicated cities or weights were selected. The signs of these differences are positive when the alternate weighting or weather yields a higher efficiency (i.e. between the solid lines in Fig. 2). For this subset of inverters, the standard deviation of changes is 0.05-0.2%. When all inverters are reviewed, the standard deviation is about twice as large as this case.

As might be expected from the typically midrange peak efficiency curves of most CEC-approved equipment, the overall trend is a reduction in weighted efficiency values relative to the existing weights. However, this trend is not universal and some products obtain higher weighted efficiencies as the DC/AC ratio increases.

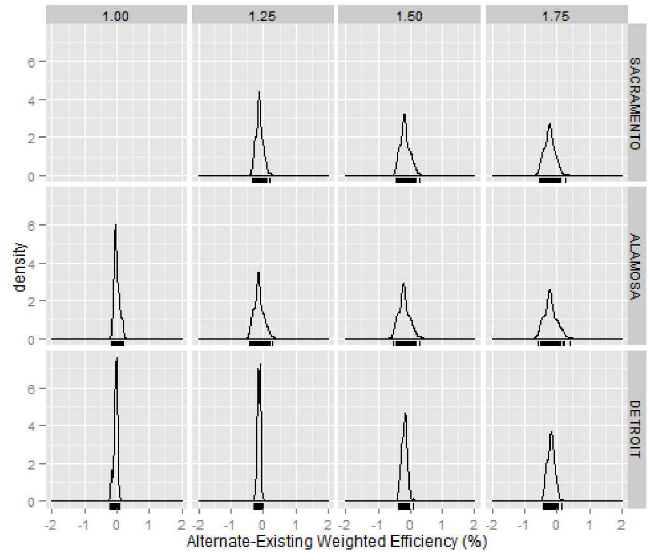

Fig. 3. Difference between weighted efficiencies by source data and DC/AC ratio for $> 100kW_{ac}$ and Circa 2010 or newer

IV. CONCLUSIONS

The development of the CEC PV inverter efficiency weighting factors has been documented, and implications for some extended weather conditions and array size adaptations investigated. The typical impact on existing inverter CEC efficiencies from selecting a lower or higher irradiance climate is less than 0.05%. The increase in weight of the efficiency at 100% of inverter power rating when larger arrays are connected to the inverter is so dramatic that the value of using weighted efficiency as a comparison metric for highly-loaded inverters is weak. In our opinion a reasonable alternative high level performance metric for inverters used with high DC-to-AC rating ratios is simply the efficiency measured at rated power, though a detailed production simulation for the target site will still be necessary to rank available equipment for a particular project.

This investigation has followed the original simplified system design approach. An additional direction could have incorporated the correlation of voltage with power level as described by Baumgartner[13] rather than the simple mean of weighted efficiencies at the different voltage levels. Also, the orientation of the array could be changed, for example to a horizontal north-south tracker. However, the magnitude of impact would be small in the first case, and the second case would emphasize the full-power efficiency even more than the high DC/AC ratio already does.

V. ACKNOWLEDGEMENTS

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