The Impact of Irradiance Time Behaviors on Inverter Sizing and Design

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Abstract—**This paper investigates the time behavior of over-irradiance events in which the photovoltaic (PV) array outputs more power than the rated power of the inverter. A new dynamic interpretation of such events is proposed and is compared to the conventional static viewpoint. Facts revealed under such dynamic view may lead to new guidelines for system integrators and inverter designers in both sizing and designing inverters. A way to extend overload operation time of inverters is also proposed.**

Keywords – Inverter sizing, short-interval irradiance data, inverter protection scheme

I. INTRODUCTION

Conventionally, PV system inverters are sized based on the monthly average irradiance data or simply by taking 70% of the nominal power P_{nom} of the PV panels [1, 2]. This conventional approach has two potential issues for inverter and PV system sizing: 1) irradiance data resolution impacts on the sizing procedure and 2) undersized inverters may not necessarily save on total life-cycle investment. For the first problem, 1 minute is suggested to be the optimum resolution in that lower resolution (such as hourly) may overlook high irradiance peaks while higher resolution (10s) often does not provide futher improvement at the cost of expanded data size [1, 3, 4]. For the second problem, a tradeoff between maximizing energy yield and minimizing inverter cost should be balanced. Burger and Ruther [1] propose that undersized inverters cause considerable energy loss under high irradiance due to overload protection of inverter. This implies that clear sky irradiance locations might have noticeably different power losses compared to cloudy locations, even when they may experience the same average daily irradiance. However, these issues have never been discussed, despite their importance in proper inverter sizing/design.

To date, the implied assumption behind inverter protection loss calculation has been that the inverters enter downscaled protection mode as soon as over-irradiance events occur, thereby causing immediate power loss. However, there might be a time delay before inverters protect themselves from over-current due to high irradiance. During such time delay, which is determined by the protection scheme of the inverter, the inverter can still handle full input power without derating.

The research contributions of this paper include the following:

- A new, dynamic viewpoint into over-irradiance events is proposed. This dynamic viewpoint is based on three factors that turn the inverter into protection mode: 1) duration time of the over-irradiance events; 2) thermal cycle of inverter; 3) overload protection scheme of inverter. These factors are case specific and location dependent.
- The findings of this paper help develop guidelines for both system integrators and PV inverter designers to choose and to design inverters for specific locations.

For system integrators, the protection scheme of inverters should be considered when choosing inverters. Overload protection schemes have substantial impacts to the total energy yields, especially under fluctuating irradiance.

For inverter designers, the overload protection scheme can be tailored for a specific location or irradiance pattern in order to maximize energy output without oversizing inverters. Furthermore, smart strategies of active cooling can be designed so that system reliability would not be degraded.

For simplicity, temperature effects of PV panels are not considered in this paper although temperature is a factor to consider in real design: temperature effect of a PV panel can affect its maximum power point and output power and is correlated with irradiance level.

II. DEFINITIONS

- Threshold irradiance (G_{Th}):

  The threshold irradiance G_{Th} is the irradiance level according to which inverters are sized, rather than the 1000W/m^2 under STC[1]. Specifically, inverters are sized according to equation (1), where G_{STC}=1000W/m^2.

$$\frac{P_{inverter,nom}}{P_{PV,nom}} = \frac{G_{Th}}{G_{STC}} \qquad (1)$$

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For example, for a STC-rated 10kW system, G_{Th}=700W/m^2 means the system is equipped with inverters rated at 7kW. Here $P_{PV,nom}$ represents the rated power (under STC) of the particular PV installation. For example, an installation with five 200W rated PV panels has $P_{PV,nom}$=1kW.

- Over-irradiance event:

  Usually inverters are not sized according to the STC-rated nominal output power of the PV panels, but according to the threshold irradiance by using (1), so that $P_{inverter,nom} = P_{PV,nom}\dfrac{G_{Th}}{G_{STC}}$. In this paper, an over-irradiance event is defined by two criteria:

a) At start time, the irradiance exceeds threshold irradiance G_{Th}.

b) At end time, the irradiance drops below G_{Th}.

c) The irradiance remains above G_{Th} from start time to end time.

- Instantaneous inverter protection mode:

  Inverter nominal input DC power ($P_{inv,nom}$) is considered the maximum input power that can be handled by this inverter. When irradiance exceed G_{Th}, the PV panels may produce more DC power than $P_{inv,nom}$ and overwhelm the inverter.

  In response to this condition, inverters have different protection schemes. In such protection modes, typically inverters reduce the input power and convert only their nominal input DC power to prevent overheating. A few inverters will shut down in protection mode, but this is less common.

- Inverter protection mode delay time/time threshold (TT):

  Inverters often have a delay time, TT, before they enter protection mode characterized by inverter design. In fact, in the inverter industry, the delay time TT, i.e. the surge rating is commonly specified in the datasheets as one operating point such as 10~20 seconds at 2~3 times of the continuous loading. For some reason, though, in the PV industry, TT is assumed zero[1], and inverter datasheets for PV systems rarely specify this delay time. This may imply that manufacturers of PV inverters can easily include, adjust or specify TT in their products so that different over-irradiance conditions can be accommodated. As this paper shows, the time under different overload conditions, especially under 1.5 times of continuous load, is important to the proper sizing of the PV inverter. This is because a significant number of over-irradiance events might occur for short instances of time that produce less than 1.5 times the rated continuous load. This makes the characterization of PV inverters different than conventional DC-AC converters: Here, PV power sources are substantially current limited by the sun's irradiance.

III. INVERTER SIZING

A. *Inverter Efficiency*

Figure 1 is a simplified PV system diagram. The output power of the PV array is assumed proportional to irradiance level, with efficiency η_{mpp} at its assumed maximum power point (MPP). The conversion efficiency of the inverter is noted as η_{inv}. The total efficiency of the system η_{Tot} is therefore $\eta_{Tot}=\eta_{mpp}\eta_{inv}$. η_{mpp} is assumed constant in normal operation region (P_{mpp}>0.2Pnom, where P_{mpp} is the input DC power of inverter at maximum power point; and P_{nom} is the nominal power input of inverter) [5]; inverter power limitation losses are included in calculating η_{inv}.

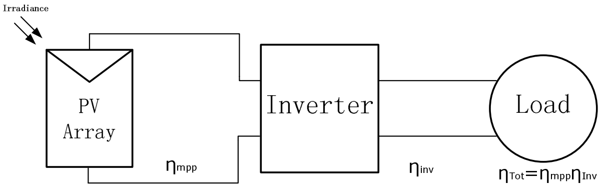

Figure 1. Simplified system diagram

Figure 2 presents typical overall inverter efficiency as a function of percentage of nominal capacity. Higher efficiency in the overloading zone is expected if inverters can withstand overloading for a longer time.

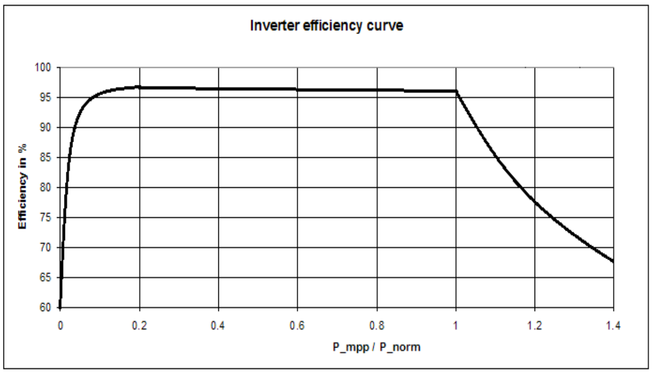

Figure 2. Typical inverter efficiency curve as a function of loading insteady-state [1, 3]

B. *Introduction to Inverter Sizing Procedures*

In most cases, restricted by irradiance condition and temperature effects of solar cells, PV systems rarely exceed their STC rated output power [3]. The rule of thumb of inverter sizing is that inverter nominal power can be approximately 30% lower than the PV array nominal DC power [1]. The downside of such a simple guideline is that it leads to considerable power loss when irradiance level is high and solar cell's temperature coefficient is small.

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[1] STC: Standard Test Condition: the testing conditions that used to measure the nominal output power of solar cells or modules: irradiantion 1000W/m^2, cell temperature 25^{o}C.

In this paper, we are proposing that during the inverter sizing procedure, the tradeoff between inverter investments and energy yield should be considered for specific locations. There are several considerations:

- Inverter cost:

  Typical inverter cost is estimated from 0.8~1.2 \$/W depends on the system size, as in the survey reports published by International Energy Agency (IEA) [6, 7]. The cost of inverter system in \$/W will slightly decrease with the increase of system size.

- Historical irradiance data

  Local historical irradiance and weather data can be used to identify the weather pattern and estimate irradiance availability and characteristics at the geographic location for future years.

  As stated in previous sections, introducing time delay before inverter enters protection mode helps recover some of the power loss in some over-irradiance events. Hence the study of irradiance data should include 1) probability of over-irradiance events and 2) the duration of over-irradiance events.

- Inverter lifetime

  For cost analysis, inverter lifetime should be taken into consideration.

  According to a report to the National Renewable Energy Laboratory (NREL), manufacturers generally feel both impossible and unnecessary to make inverters last longer than 15 years. In this context, typical inverter lifetime is between 5-10 years [8].

- Local electricity rates

  Local electricity rates are used to quantify the energy loss due to undersizing of inverters into cost.

IV. EVALUATION OF POWER LOSS

A. *Solar Irradiance Data*

Data used for analysis and discussion in this paper are available from the Solar Radiation Monitoring Laboratory, University of Oregon. For the discussion in this paper, the data are measured and recorded once every minute, in Eugene, OR, 2009. They are the horizontal global irradiance measured by one broad band sensor and six narrow band sensors [9]. (Similar analysis could be performed for other geographic locations if irradiance data is available.)

B. *Effects of Time Threshold (TT)*

Time threshold (TT) in this paper is defined as the protection time delay when input power of inverter is 150% of its nominal power. For example, if TT= 2 mins and G_{Th}=700W/m^2, when the irradiance is around 1000W/m^2, the inverter can handle the over-irradiance without entering protection mode for 2 minutes. Irradiance higher or lower than 1.5G_{Th} decreases or increases the actual time delay, respectively.

It should be noted that when irradiance is well below G_{Th}, the inverter cools down and would be able to operate for a longer time during the next over-irradiance event occurs. Similarly, if over-irradiance events occur frequently, the protection time delay would be shortened. The simulation presented in this paper has not included such effects.

Assume that we size the inverter with G_{Th}=700W/m^2, the common wisdom would be that every watt exceeding 700W/m^2 was wasted since the inverter would limit the power output of the PV array in accordance to 700W/m^2.

As an example (Eugene, OR in 2009), Figure 3 presents a histogram of time duration of over-irradiance events. Notice that more than 25% of over-irradiance events (437 out of 1661) last less than 1 minute and more than 15% (252 out of 1661) last less between 1 and 2 minutes. This adds up to 40% of all over-irradiance events. This means that, if the inverter has a 2-minute overload protection delay, it would not waste energy due to entering protection mode in most of the over-irradiance events during the 2 minutes. If TT can be further increased, then even more energy can be recovered.

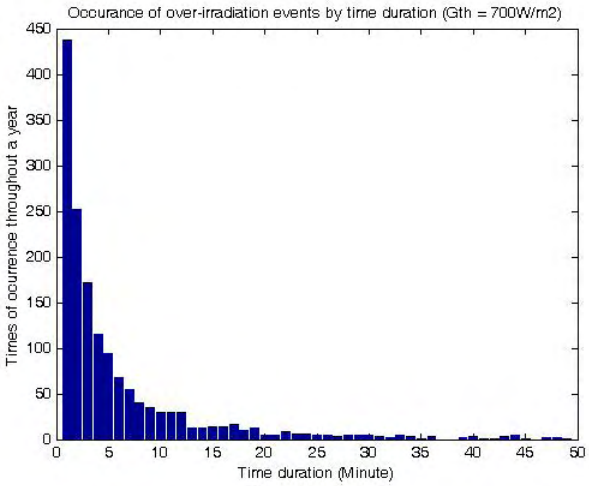

Figure 3. Occurrences of over-irradiance v.s. time durations Eugene, OR, over a 1-year period

Figure 4 shows the comparison between cases with and without the 2-minute protection time delay. Dark areas depict the extra power rescued by this time threshold, while the lightly shaded areas represent the wasted power. This is a zoomed graph and the time span is 250 minutes. From t1 to t2, although the irradiance is beyond nominal level, the inverter might still output additional power for 2 minutes. The inverter would then reduce power of the PV panels to match its nominal power from t2 to t3, during which the extra irradiance is wasted. Similar procedure occurs during t4 to t6 and t7 to t9. In this specific data set (Eugene, OR, 2009), the improvement of energy loss is 19.67% year-wide (87.26kWh energy loss with TT=0 min vs 77.79kWh energy loss with TT=2 mins). The amount of improvement is case and location dependent. Even for locations with the same average irradiance, more energy can be saved using this scheme in cloudy areas; while in areas with a lot of clear days and sunshine, increasing TT might be less effective. A cost analysis is needed to determine the strategy to achieve optimum cost effectiveness.

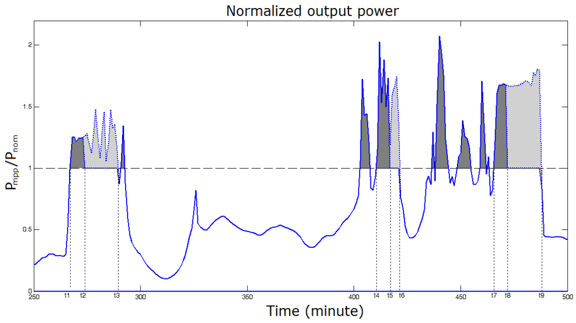

Figure 4. Normalized output power with and without protection delay for a partly couldy day, in Eugene, OR – 250 minutes of data shown

C. Cost analysis

As an example, we will size an inverter for a 10kW PV system built in Eugene, OR. With the irradiance data of Eugene in 2009, we can run a cost analysis to determine the best parameters G_{Th} and TT. We assume that the inverter's conversion efficiency is 95% and that inverter cost is 1 \$/W [6, 7]. We further assume that inverter lifetime to be 10 years and local electricity rates to be around 0.20 \$/kWh. For a first demonstration, we size the inverter using G_{Th}=700W/m^2 and TT=2 mins.

1) For G_{Th}=700W/m^2, inverter size would be 7kW, then inverter cost would be \$7,000, which saves \$3,000 from sizing with G_{Th}=G_{STC}=1000W/m^2.

2) According to part B of this section, total energy lost for TT=2 mins would be 778kWh throughout the year of 2009;

3) The equivalent cost for the energy loss with local electricity rate would be \$155.6 per year;

4) In the 10-year lifetime of the inverters, total energy cost due to undersizing would be \$1556;

5) Other expenses such as extra cooling fans and control circuits of the inverters should also be considered.

6) To sum up, undersizing scheme would help saving an estimate of more than \$1,000 on inverter investments.

7) For the protection delay alone, the 2-minute delay scheme would save \$146 from the non-delay case, which is around 10% of the total savings.

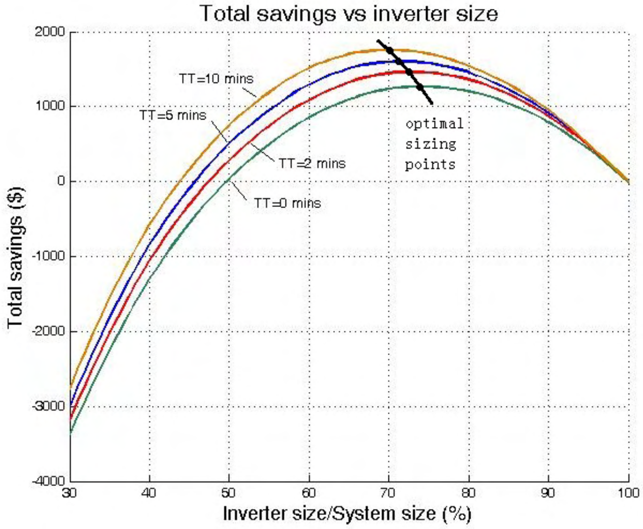

Figure 5. Total inverter cost savings vs inverter size (or G_{Th}) for different TT

Both parameters G_{Th} and TT directly influence the final savings in inverter cost. "Savings in inverter cost" here refers to the reduced investment on inverters when applying the undersizing and protection-time-delay scheme.

Note that the optimum point of inverter size might change with different time thresholds. In Figure 5, the accurate optimum point is moving leftwards when time threshold TT is increased. Specifically, when TT=0, the optimum inverter size is 740W/m^2 while it would be 700W/m^2 when TT=10 mins.

As Fig. 5 shows, when inverter is undersized over a certain limit (for example, around 500W/m^2 for TT=0), the cost of energy loss would exceed the saving on inverter investment. In this specific case (Eugene), if the inverter is undersized too much, for example, at G_{Th}=300W/m^2, the cost for energy loss would exceed the saving on inverter cost. If G_{Th}=800W/m^2, the inverter might have been oversized than necessary.

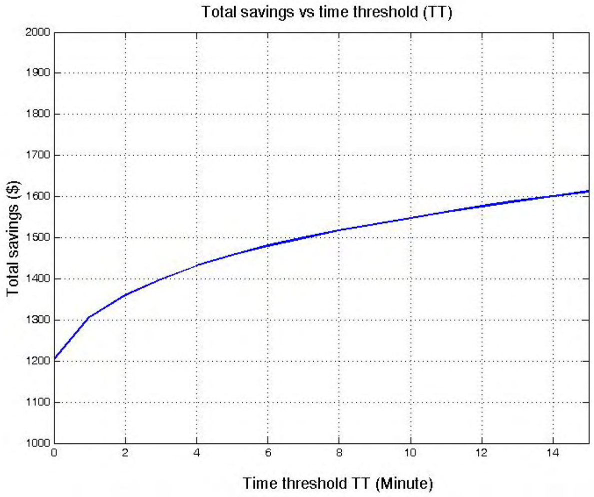

Figure 6. Total inverter cost savings vs time threshold (TT) when G_{Th}=700W/m^2

Figure 6 shows the relationship between TT and the total savings. As TT increases, more energy under over-irradiance can be recovered. For a given inverter size, 1~2-minute protection delay would provide considerable amount of recovered energy. However, it might be difficult and costly to further improve TT.

D. New inverter protection design consideration

The histogram in Figure 4 might inspire inverter designers to tailor the overload protection schemes for a specific delay time in an inverter. Development of inverters' cooling schemes might be a direction of achieving this goal. Usually a fan is not a preferred option due to lower reliability. However, a fan can be added to a convection cooling inverter to provide additional thermal performance during overloading. A possible control scheme might be turning on the fan only when over-irradiance event is observed and for 2 minutes at maximum. Events below 2 minutes count only around 1000 minutes, which is translated into fan duty ratio of less than 0.2% in a year. In this context the reliability would not be compromised while the cooling is improved under overload conditions.

V. CONCLUSION

Commonly inverters are capable to handle power surges for a short time. This surge capability is currently not considered in PV inverter sizing. In this case, expected power capability would be lower than real available power and might affect the tax credit. For inverter design, a simple addition to inverter's cooling system helps improve inverter energy yield while keeping comparatively low inverter cost. A dynamic viewpoint into over-irradiance events based on high resolution data shows that PV inverter sizing procedures might be influenced by cloud and weather patterns in different geographic locations.

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