Optimum Inverter Sizing in Consideration of Irradiance Pattern and PV Incentives

Song Chen* Peng Li David Brady Brad Lehman*
Department of Electrical and Computer Engineering
Northeastern University
Boston, Massachusetts, USA

Abstract— **This paper proposes a general method of sizing the inverter for a PV system. The method evaluates effects of PV incentive policies, inverter efficiency curves, and inverter protection schemes on optimum inverter sizing through system-level cost analysis. Specifically, different scenarios of PV incentives are discussed and compared to show that the optimal inverter size varies notably by location and context.**

I. INTRODUCTION

Conventionally, PV system inverters are sized based on the rated power of the PV panel installation. There, generally, are two typical methods to sizing the inverter: 1) The inverter is sized to approximately match the nominal PV array installation, i.e. a 10kW rated (at STC) PV installation is sized with a 10kW inverter, or 2) the inverter is downsized with the typical rule-of-thumb to take 70% of the nominal power $P_{PV,nom}$ of the PV panels [1-4]. In this case, the same 10kW is sized with approximately a 7KW inverter. The rationale of downsizing the inverter is that irradiance levels in real installations only occasionally reach irradiance levels of the STC conditions ($1000W/m^2$ at AM=1.5). Therefore, the additional investment on the inverter used to match the inverter size to the array's "rated" power might not be recovered over the life-expectancy of the inverter. There is a tradeoff between maximizing energy yield and minimizing inverter cost.

Only recently have there been analytic qualifications and conjectures as to what might be the optimal inverter size [2, 3]. For example some researchers propose that undersized inverters cause considerable energy loss under high irradiance due to overload protection of inverter [2]. In this case overload refers to over-irradiance, a condition in which the input power of inverters is more than their nominal input power. This implies that clear sky irradiance locations might have noticeably different power yield compared to cloudy locations, even when they may experience the same average daily irradiance. Further, it is shown that the characteristics of the inverter protection scheme also strongly influence the decision on inverter sizing [5], i.e. whether the inverter has time delay before entering protection, thermal fold-back, or simply shuts down in over-current protection modes.

The purpose of this paper is to provide precise and realistic considerations into the optimization of inverter sizing for PV installations. In particular, we include in the cost/optimization analysis

1) *Influence of different irradiance patterns* – Even for PV systems of the same size, the economically optimal inverter size can differ given different irradiance patterns. This paper compares such effect in two geographic locations that have very different irradiance patterns. One location is characterized as cloudy area with low irradiance most of the time; the other has the irradiance mostly distributed almost equally at the high level region. The analysis shows that the undersizing scheme is more justified in the low-irradiance area in that there will be less over-irradiance events and hence less energy waste.
2) *Influence of government incentive on PV installations* – This leads to perhaps the most surprising result that has not been mentioned ever in the literature: Different types of incentives will lead to substantially different inverter sizing investment to optimize the return on investment. For example, in the USA, some states offer Performance Based Incentives (PBI) based on the actual power produced by the entire installation. Other states have incentives that are not performance based and are only based on cost or wattage of the installation. When there are substantial PBI incentives, the cost

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of a larger inverter can be justified. Otherwise, downsized inverters might be selected.

3) *Inverter power efficiency curves* – Previous research assumed PV inverters operated at constant efficiency, independent of the load. This is unrealistic, particularly in low power or scaled-back over-power protection schemes. Our approach is to take realistic inverter efficiency curves (from independent test lab results [6]) and include this data into the cost-optimization analysis.

4) *Different inverter protection schemes* - 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. However, in order to achieve precise cost analysis, high resolution of time-sampled irradiance data must be used to understand the energy that may be recovered.

Each of the above categories directly influences the recommended size of the inverter to maximize the return on its investment. We demonstrate these concepts through case analysis of 10kW PV array installations simulated for Eugene, Oregon and Las Vegas, Nevada. The analysis utilizes experimental horizontal irradiance data sampled each minute for an entire year of 2009. The measured irradiance data are available from the Solar Radiation Monitoring Laboratory, University of Oregon and University of Nevada at Las Vegas. As we show in the examples, proper undersizing of the inverter may return up to 18% on inverter investment depending on geographic location.

II. BACKGROUND

This section introduces the information used for analysis in this paper including inverter sizing strategy, cost analysis and data source.

A. Inverter sizing

Inverter takes a considerable portion of PV system capital cost. A common tradeoff in inverter sizing is the balance between energy yield and inverter investment. Conventional practices are to 1) let nominal input power of inverter to approximately match the nominal output power of PV array: $P_{inv,nom} \approx P_{PV,nom}$; 2) undersize inverter to 70% of PV array size: $P_{inv,nom}=70\%P_{PV,nom}$ [2, 3], Both practices are empirical and might not be sizing the inverter optimally with respect to cost and return analysis.

If $P_{PV,nom}$ is rated under Standard Test Condition (STC)[1] with irradiance $G_{STC}=1000W/m^2$, inverter size can be described as a nominal irradiance level G_{Th} or the ratio between $P_{inv,nom}$ and $P_{PV,nom}$, denoted R:

$$\frac{P_{inv,nom}}{P_{PV,nom}} = \frac{G_{Th}}{G_{STC}} = R \tag{1}$$

where

- $P_{inv,nom}$ is DC input rated power of inverter
- $P_{PV,nom}$ is rated PV installed power

For example, for a STC-rated 10kW system, with approach 1, $G_{Th}=1000W/m^2$ and the inverter is rated at $P_{inv,nom} \approx 10$kW; while with approach 2, $G_{Th}=700W/m^2$ and the inverters is rated at $P_{inv,nom} \approx 7$kW.

B. Cost analysis

The determination of optimal inverter size is based on the PV-system-level cost analysis, which includes component cost, incentives, irradiance data, etc. That is, the overall cost can be expressed as (2)

$$\begin{aligned}\text{Total cost} = {} & \text{PV cost} - \text{Tax incentives} - \text{Rebate}\\ & + \text{Inverter cost}\\ & + \text{Other costs}\left(\text{labor, structuring, wiring, etc.}\right)\end{aligned} \tag{2}$$

This paper assumes inverter cost as \$1/W [6, 7], PV cost as \$4/W [8] and other costs as \$3/W [9]. Further, it is assumed that inverter lifetime is 10 years and that local electricity rates to be around \$0.2/kWh (Boston, MA, residential rate).

The “effectiveness” of an undersized inverter is analyzed by calculating “Total savings,” compared to an inverter based on $P_{inv,nom}=P_{PV,nom}$, i.e. the baseline case is when $G_{Th}=G_{STC}=1000W/m^2$ or R=1. For convenience of statement, we are using R to describe the size of inverter. The analyses consider inverter cost, inverter efficiency, and cost for energy loss, due to excess irradiance, at given performance-based incentive PBI level. For any inverter size $R=r,\ \left(0 \le r \le 1\right)$, The total savings can be expressed as equation (3):

$$\begin{aligned}\text{Total savings}\big|_{R=r} = {} & \left(\text{total cost}\big|_{R=1} - \text{total cost}\big|_{R=r}\right)\\ & - \text{cost for energy lost}\big|_{R=r}\end{aligned} \tag{3}$$

In particular, the cost for energy lost is calculated using (4), by assuming that the inverters work under

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[1] STC: Standard Test Condition of PV modules: irradiance = 1000W/m^2, cell temperature = 25°C, air mass = 1.5

downscaled protection mode limiting their maximum power:

$$\text{Cost for energy lost}|_{R=r} = \int_{\substack{\text{start of}\\ \text{over-irradiance}}}^{\substack{\text{end of}\\ \text{over-irradiance}}} \left(\text{PV output}|_{\text{MPPT}} - \text{PV output}|_{P_{inv,nom}} \right) dt \times \left(\text{electricity rate} + \text{PBI} \right) \tag{4}$$

Equation (4) quantifies the value of wasted energy due to the excess solar energy with respect to the capability of inverters in each over-irradiance event. In Equation (4), PBI denotes the Performance-based incentives, which will be discussed in Section IV.

III. THE EFFECTS OF IRRADIANCE PATTERNS

The sizing strategy of PV inverter might be influenced by the irradiance patterns of specific locations. Figure 1 shows the distribution of horizontal total irradiance throughout year 2009 for two different locations, Eugene, OR and Las Vegas, NV. Each occurrence represents a minute time interval of data sampled at the irradiance level. The horizontal axis represents the irradiance level; and each bar in the histogram describes the number of minutes at which the irradiance falls into a 50W/m^2 span. Hence, Figure 1 depicts the distribution of the minute data at different irradiance levels, i.e, the irradiance patterns of both geographic locations.

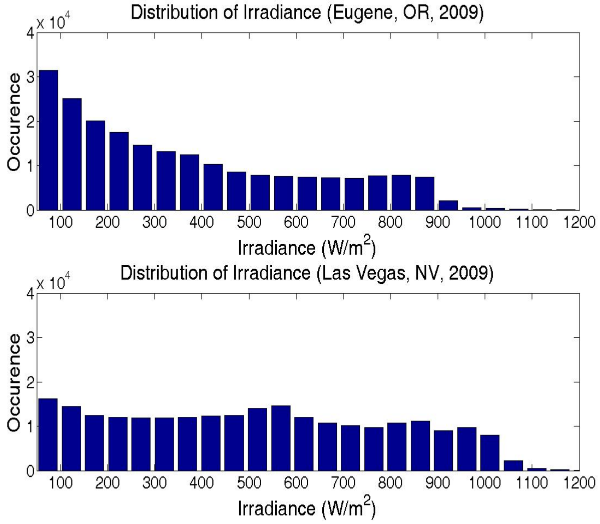

Figure 1. Distribution of total horizontal irradiance data (data for Eugene, OR, and Las Vegas, NV, 2009)

By fixing the amount of incentives, we extract the effects of irradiance patterns on the PV inverter sizing strategies. Figure 2 shows the results from cost analysis in terms of total savings. In Figure 2, both performance-based incentives (PBI, see Section IV) and inverter protection delay (TT, see Section VI) are zero; the inverter is scaled down to rated power in over-irradiance conditions (fold-back protection, see Section V). Realistic inverter efficiency data has been used in the cost analysis (See Figure 4 and [10]) The results show that the optimum inverter size would be substantially affected by irradiance patterns. In Eugene, the irradiance distribution is weighted heavily to instances of low irradiance, representing a low irradiance climate in this region; while in Las Vegas, the distribution is weighted more to instances of higher irradiance around 800~1000W/m^2. The results of cost analysis turn out that the optimum point inverter size is different in Las Vegas than in Eugene (optimal R$\approx$0.7 for Eugene, versus R$\approx$0.85 for Las Vegas), even for the same PV system with the same rate of incentives.

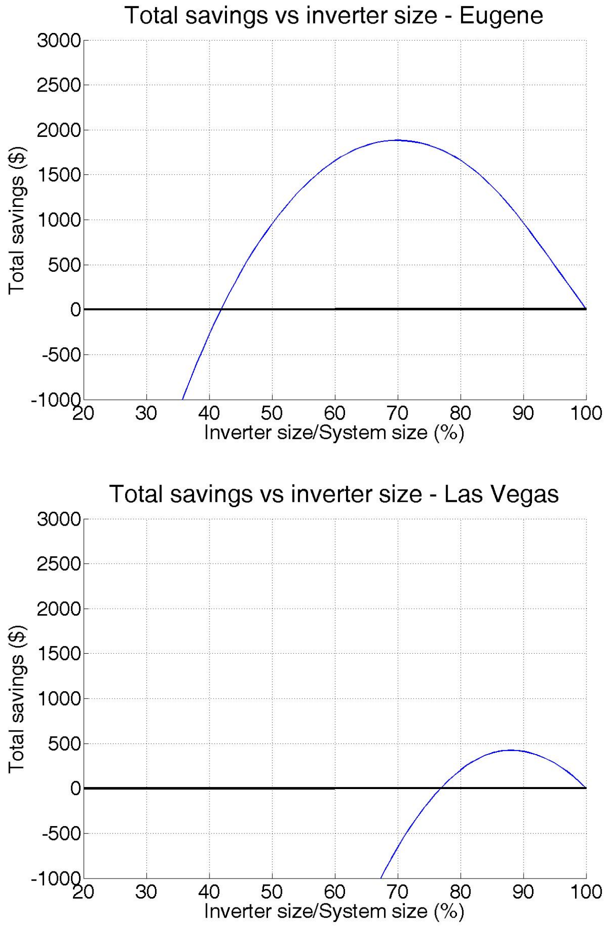

Figure 2. Optimum inverter size for a 10kW system at Eugene, OR and Las Vegas, NV. Based on year 2009 data. Account for 10 year period

As shown in Figure 2, based on 30% of Federal tax incentive and no performance-based incentive, for the total savings of the 10kW PV system ($10,000 inverter cost), the peaks are at ~$1,800 when $R \approx 0.7$ in Eugene; and at only ~$300 when $R \approx 0.85$ in Las Vegas.

Note that certain inverter sizing schemes might cause the customer to gain negative savings, i.e., to lose money. For example, in Eugene, if $R<0.4$, which is a less practical number in inverter sizing, the total savings would be negative; while in Las Vegas, the turning point is around 0.75. Furthermore, conventional choice of $R=0.7$ would lose money in Las Vegas – clearly, $R=0.7$ is not viable for every geographic location.

To summarize the effect, in cloudy areas that have the irradiance distributed heavily around the low irradiance region, the strategy of undersizing the PV inverters can be better justified in that even with the performance-based incentives, the reduction in inverter costs can compensate for the energy lost due to over-irradiance. The undersizing strategy may not be necessary in areas that are not frequently shaded by clouds: as the performance-based incentives goes higher, the cost of energy lost could easily offset the savings on inverter cost.

IV. PV INCENTIVES

In the USA, PV incentives, granted by both the Federal and State governments, might have considerable effects on inverter sizing. There are generally three categories of PV incentives: a) tax credits; b) system purchase rebates and c) performance-based incentives. The current state of PV incentive programs is summarized in Table 1.

TABLE I. CURRENT (2010) PV INCENTIVE PROGRAMS [11]

Incentive Type	Number of States	Range of Amount	Range of Cap
Tax credits	26	15%-50% of system cost or PV wattage	$1,000-$25,000
State rebates	33	$0.75-$3/W nominal DC power	$2,000-$500,000
Performance-based incentives (PBI)	33	$0.0025-$1.5/kWh	N/A
USA Federal tax credit		30% of system cost	No limit

As for tax credits, there are income tax credits and sales and property taxes exemptions. This paper reviews effects of income tax credits only, as this kind of tax incentives is more general for most PV customers. Note that although state income tax credit varies by state, the United States allows 30% federal tax credit for the expenditure of a PV system with no upper limit [11].

TABLE II. OPTIMUM INVERTER SIZE AND (10 YEAR) SAVINGS WITH DIFFERENT PERFORMANCE-BASED INCENTIVES FOR EUGENE, OR

PBI ($/kWh)	Optimum GTh (W/m2)	Maximum savings ($)
0	0.70	1900
0.1	0.77	1500
0.3	0.83	1200
0.6	0.86	1000

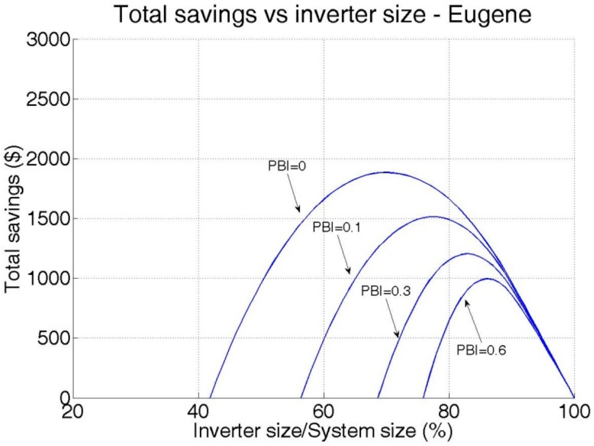

Figure 3. Optimum inverter size for a 10kW system at Eugene, OR, based on year 2009 data. Savings are for 10 year period.

The effect of PV incentives on sizing strategy can be summarized as:

1) In most states, the income tax incentives are based on total system cost, including PV panels, inverters, balance of system, and labor. Inverter sizing strategy might have to consider these policies in a specific location. Larger inverters permit more energy yield and more tax credits. Such effect may be less important when the system size is large and the incentive cap is met.

2) Most of the state rebates are based on rated DC power of PV arrays, which implies, with the same installed PV system size, a smaller inverter can reduce overall system expenses while permitting the same amount of state rebates.

3) In some states a portion of incentives are granted based on performance of the system. Generally this type of incentive is high compared to local electricity rates. It might notably affect the overall optimum inverter size as shown in Figure 3 and Table 2. Larger inverters might be chosen to produce more energy in order maximize PBI

instead of choosing a smaller inverter to save on initial costs.

Table 2 and Figure 3 show the cost analysis with PV incentives. For simplicity, the PV size is fixed at 10kW. It shows that the optimum inverter size varies with local irradiance patterns as well as the incentives policy, contrary to commonly suggested R=0.7. As shown in Figure 3, an optimal inverter selection without PBI might lose money with PBI incentive. That is, the high performance-based incentives rate would encourage choice of a larger size inverter due to the returns on the extra energy converted.

V. INVERTER EFFICIENCY

Inverter efficiency is another factor that affects the optimum size. Different sized inverters under the same irradiance would have different efficiency. Inverter efficiency η_{inv} usually varies with inverter load. Figure 4 presents the typical inverter efficiency (average efficiency of several commercial PV inverters, as reported in [6, 10]). Also, its efficiency during TT (TT is defined as the protection delay time of inverter, see Sec. VI for detail) is also considered.

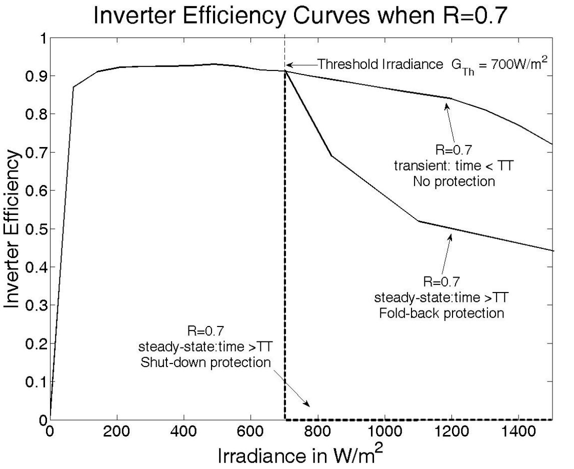

Figure 4. Typical inverter efficiency curve as a function of load (irradiance) [12]

When irradiance is below G_{Th}, i.e., the output DC power from PV panels does not exceed the rated input power of the inverter ($G \leqslant G_{Th}$, $P_{PV} \leqslant P_{inv,nom}$), the inverter's conversion efficiency can be written as:

$$\eta_{inv} = \frac{P_{AC,inv}}{P_{PV}} \tag{5}$$

where $P_{AC,inv}$ is output AC power of the inverter and P_{PV} is the PV power output. Equation (5) for inverter efficiency can also describe the case when the irradiance is above G_{Th} but lasts for a short transient less than the inverter's protection delay time TT. That is, within this transient time TT, the inverter does not downscale the input power in its protection mode and all excess input power is converted.

While in the case that $G>G_{Th}$ and t>TT, the inverter's efficiency curve, shown as the thin solid curve in Figure 4, decreases after the irradiance G is above G_{Th} (700W/m^2 in the case). Then we can define maximum rated efficiency of the inverter as:

$$\eta_{rated} = \frac{P_{AC,nom}}{P_{inv,nom}}$$

where $P_{AC,nom}$ is the AC output power of the inverter when its DC input is $P_{inv,nom}$

Then for over-irradiance event $P_{PV} = P_{inv,nom} + \Delta P_{dc}$, the efficiency can be written as

$$\eta_{over-rated} \approx \frac{P_{ac,nom}}{P_{inv,nom} + \Delta P_{dc}} \approx \frac{\eta_{rated}}{1 + \frac{\Delta P_{dc}}{P_{inv,nom}}} \tag{6}$$

ΔP_{dc} denotes the extra power that the PV array produces and feeds into the inverter under irradiance higher than G_{Th}. As the irradiance goes higher, ΔP_{dc} increases, causing the efficiency under over-irradiance ($\eta_{over-rated}$) to decrease, as shown in Figure 4.

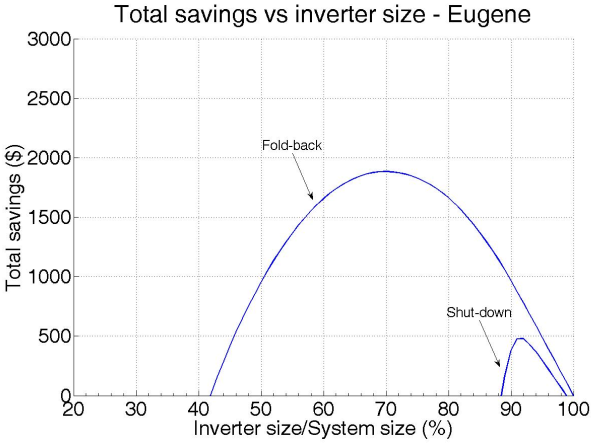

Figure 5. Optimum inverter size for a 10kW PV system at Eugene, OR. Different inverter protection schemes: fold-back vs. shut-down

To protect the inverter from overload, there are two major schemes: 1) Fold-back: inverter converts only the rated power by forcing the PV system to work at a non-maximum-power point of the PV system; and 2) Shut-down: inverter shuts down when overloading occurs and turns back on when load is within limit.

Figure 5 compares two different schemes of inverters' overload protection. The fold-back scheme outperforms the shut-down scheme in terms of total savings. Because in fold-back protection mode, inverters are converting rated power rather than nothing during overload conditions, i.e. over-irradiance conditions in this paper, reducing energy lost.

VI. INVERTER PROTECTION DELAY

A. *Effects of protection delay*

Inverter's protection delay time is commonly designed by the inverter industry. During this delay time, some energy loss due to high irradiance can be recycled. This section discusses the effect of TT in inverter sizing. 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 R=0.7, when the irradiance is around 1050W/m^2, the inverter would ideally be able to 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 proportionally. This, of course, leads to the two different efficiency curves of an inverter shown in Figure 4: 1) the inverter efficiency for the brief time period less than TT before the inverter protection activates and 2) the inverter efficiency when over-irradiance lasts longer than TT and power scale-down or inverter shut-down has been executed.

Past analysis had assumed the inverter immediately enters protection mode and that every watt exceeding G_{Th} was wasted since the inverter would limit the power output of the PV array at G_{Th} [2, 3]. In this paper, we consider that the inverter can operate in over-irradiance for a brief time period, as described above; but at reduce efficiency as in Figure 4. This means the inverter does not waste energy due to entering protection mode in for short over-irradiance events.

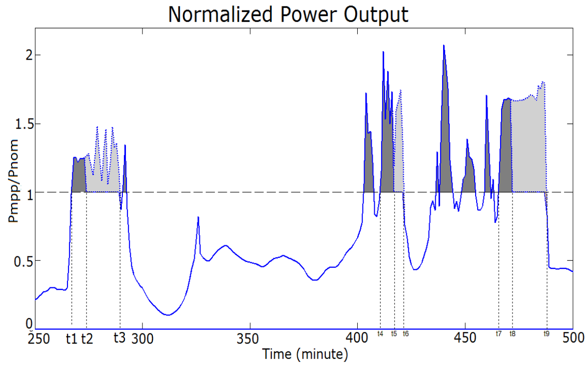

Figure 6. Normalized output power with and without protection delay

Figure 6 shows the comparison between cases with and without the protection time delay TT=(t2-t1) mins. Dark areas depict the extra power rescued by this time delay, 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 can still output the extra power for TT minutes. The inverter downscale the PV panels to match its nominal power from t2 to t3, during which the extra irradiance is wasted. Similar procedure happens during other over-irradiance events. Spikes that last less than TT minutes are not interrupted by the inverter.

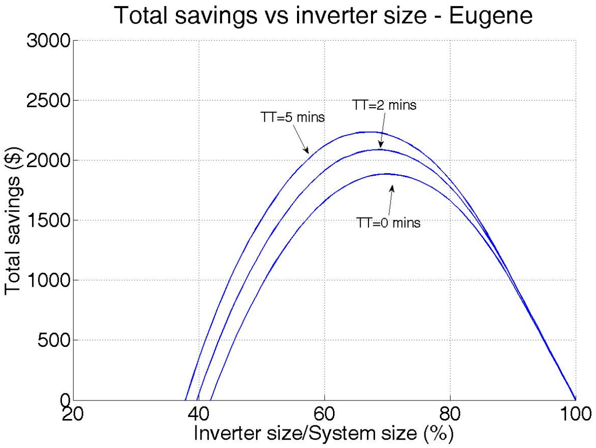

Figure 7. Total inverter cost savings vs inverter size (R) for different TT of Eugene, OR. (No performance-based incentives)

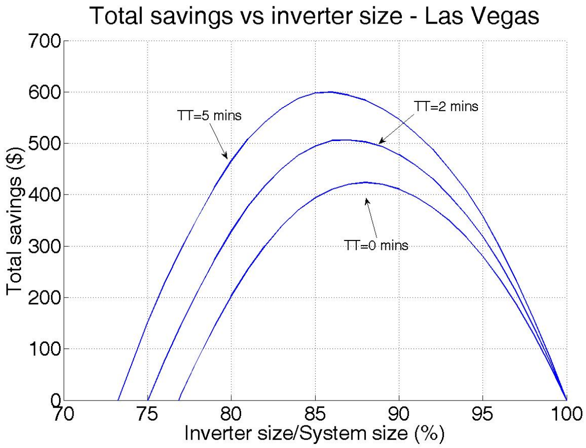

Figure 8. Total inverter cost savings vs inverter size (R) for different TT of Las Vegas, NV. (No performance-based incentives)

Figure 7 for Eugene, OR, shows the total savings with different TT value (TT=0, 2, and 5 mins). It shows in Figure 7 that in 10 years' life span, about $400 more total savings are realized with TT=5 mins compared to TT=0 mins. The amount of improvement is case and location dependent. Figure 8 is the Las Vegas version of Figure 7; in sunny areas like Las Vegas, the improvement of savings is $200 from TT=0 mins to TT=5 mins. In sunny areas, the over-irradiance events usually last for a longer time without fluctuation. The result is the inverter does not have time to cool down and would be in protection mode in most over-irradiance minutes. In cloudy areas, many over-irradiance events only last for a few minutes thereafter the irradiance drops below G_{Th} for a while. This kind of fluctuation permits the inverter to cool down; so another protection delay TT can be realized in the next over-irradiance event.

B. *Effects of inverter cooling system*

The facts revealed in Figure 4 and 5 imply that it might be desirable to extend the inverter's protection delay time at a reasonable cost. Development of inverters' cooling schemes would be the direction of achieving this goal.

Usually a fan is not a preferred option due to its reliability issues. However, a fan can be added to a convection cooling inverter to provide additional resistivity to overloading. A proposed control scheme might be turning on the fan only when over-irradiance event is observed and for TT minutes at maximum. For example, in Eugene, OR, over-irradiance events below 5 minutes count only 10575 minutes, which is translated into fan duty ratio of less than 2% in a year. Typically the cooling fan's lifetime is considered to be 3 years with 100% duty ratio. With such a low duty ratio in this application (~2%), the fan should serve the 10-year expected lifespan of the inverter if TT was selected to be 5 mins. In this context, the reliability would not be compromised while the cooling is improved under overload conditions. If the fan does fail, the inverter controller can reset the protection scheme to TT=0 with no harm to the system.

VII. CONCLUSIONS

A more general method of sizing the inverter for a PV system considering effects of irradiance pattern and incentives policies is proposed. The actual optimum inverter size is mainly affected by irradiance patterns (geographic locations) and performance-based incentives (PBI). Whether the location is sunny or whether there is high PBI may affect the choice of optimum inverter size. Inverter's overload protection scheme, including the protection delay TT and the protection methods (fold-back or shut-down) is another factor to be considered.

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