PERFORMANCE OF PV INVERTERS

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ABSTRACT

The inverter is a major component of photovoltaic (PV) systems either autonomous or grid connected. It affects the overall performance of the PV system. Any problems or issues with an inverter are difficult to notice unless the inverter totally shuts down. In this article, the characteristics of inverters are discussed along with some of the problems that can occur but are not often spotted. It is also shown that high resolution time monitoring may aid in identifying issues that otherwise would go unnoticed. The data have been collected under actual operating conditions and different times of the year allowing for a better overview of their performance as a function of irradiance or temperature.

1. INTRODUCTION

For any grid tied photovoltaic (PV) system, the inverter is the essential piece of equipment that changes the direct power (DC) from the PV array to alternating power (AC) used in the electrical grid. Not only does the inverter convert DC to AC power but it also regulates the PV system. The electronics that perform this task utilize special algorithms known as maximum power point tracking (MPPT) algorithms.

The inverter affects the overall performance of the photovoltaic (PV) systems and problems concerning inverters are difficult to notice unless the inverter totally shuts down. In this article, the characteristics of several inverters are discussed along with some of the problems encountered when monitoring PV systems.

Some of the inverters covered in this article are several years old and have already been replaced by new models with improved technologies. We hope to get access to new models for comparison.

First, the data used in this study are discussed followed by a brief overview of inverters. The characteristic performance of the inverters is then described followed by a discussion of issues that have occurred.

2. THE DATA

The Alternative Energy Consortium (AEC) PV test facility consists of eight PV systems with four different inverter and a variety of photovoltaic modules. The PV systems range in size from 2.5 to 3.6 kilowatts. The purpose of the facility is to learn how the various modules perform with a variety of inverters and to learn about the performance of grid-tied photovoltaic systems. AEC teamed with the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) to monitor and analyze the performance of the systems [1].

The data monitoring equipment consists of two Kipp & Zonen SP Lite pyranometers, one horizontal and one in the plane of array. The meteorological measurements are the wind speed and ambient temperature. The DC current and voltage into the inverters and AC power output are measured using Ohio Semitronics transducers. The temperature of one of the modules is also monitored. The data are recorded by a Campbell Scientific data logger that samples the data on a one second basis and stores the data in 5-minute averages.

The pyranometers were calibrated at the UO SRML in Eugene against instruments with calibrations traceable to

Fig. 1: Inverters at the AEC PV Test Facility. Two SMA 2500s, one Fronius 2500, two SunVista 3500s, and three PV Powered 2800s.

NREL and hence to international standards. The absolute accuracy of the pyranometers is ± 5% with the largest uncertainties coming at large zenith angles. The Ohio Semitronics voltage and current transducers have a specified uncertainty of ±0.25% at full scale and the AC power output has an uncertainty of ±0.5% at full scale. The temperature transducers have an uncertainly of ±0.5ºC. The data logger has an accuracy of ±0.05% of full scale range.

The AEC PV test facility is located within a mile of the UO SRML solar monitoring station. This station collects high quality solar radiation data and this data can be used to calibrate the pyranometers at AEC during clear days.

Data from other sites are also presented in this article and the equipment is similar to that used at the AEC PV Test Facility. The values reported do have uncertainties of a percent or two as these are field measurements and there can be many factors that affect the measurements. In addition, the findings are for individual inverters and do not necessarily correspond to all similar models. However, the overall trends that are reported in this article are similar between the individual inverters monitored. More information about the data and the data itself can be found at http://solardata.uoregon.edu/SolarData.html.

3. INVERTER BASICS

Inverters transform DC power from the PV array into AC power for the grid. Since solar arrays behave like batteries powered by the sun, inverters have to manipulate the DC voltage and current to maximize the power produced by the arrays. Power is the product of current times voltage and the maximum power is obtained when the product of the current and voltage is the greatest. A generic I-V curve

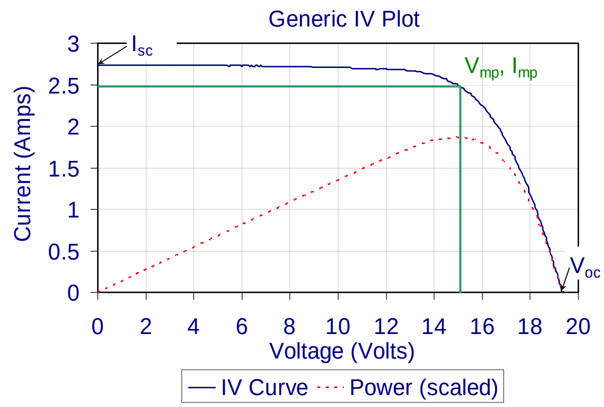

Fig. 2: Generic IV curve for a photovoltaic module. Module power equals current times voltage. The dotted line is the DC power (scaled to fit on plot) plotted for various voltages. The max power point is labeled and can be considered as the rectangle with the largest area that can be obtained using the current and voltage values on the curve.

is shown in Fig. 2 where the maximum power point is easily identified along with the open circuit voltage (V_{oc}) and short circuit current (I_{sc}). Several MPPT algorithms are available for this purpose and each manufacturer may apply any of them (e.g. Hohm and Ropp [3], Yu et al. [2]).

As the voltage increases or decreases from the max power point, the power from the array decreases as compared to the maximum power output possible. Software or hardware in the inverter senses when the maximum power specification output of the inverter is about to be exceeded, and instructions are sent to the max power point tracker to decrease the amount of power produced.

The inverters use the grid to synchronize their AC output power and to set the AC output voltage. Inverters are constructed so that if the AC voltage sensed by the inverter from the grid gets outside a specified range, the inverter will shut down immediately. Typically an inverter shuts down for about 5-minutes if it senses the grid going down. This is a safety precaution but not the only one that prevents inverters from sending power into the grid if the grid fails. Inverters carry several anti-islanding features that are of paramount importance for safety reasons (Xu et al. [4])

Inverters may operate indoors or outdoors. If inverters are located outdoors, they should be provided some shade from direct sunlight. Often inverters will have heat fins that help cool the inverters and good airflow over these heat fins should be maintained.

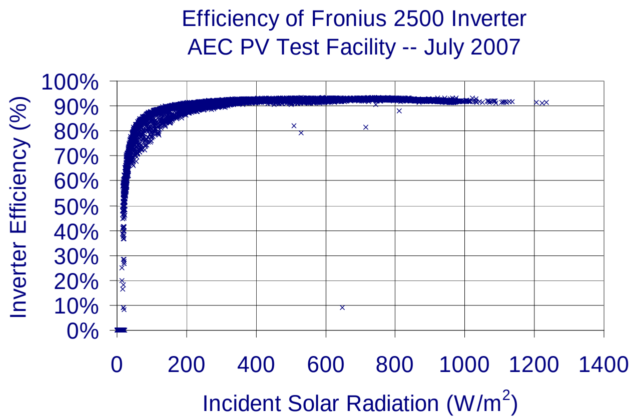

Fig. 3: DC to AC conversion efficiency of a Fronius 2500 inverter plotted against incident solar radiation. The data in the plot comes from the AEC PV Test Facility in July, 2007. The 5-minute AC output power data values are divided by input DC power values.

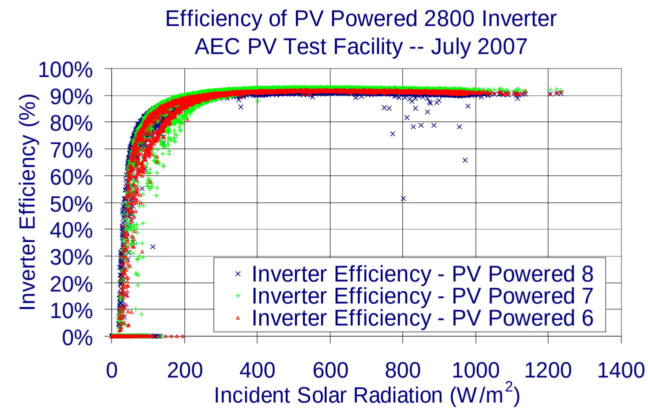

Fig. 4: Efficiency of three PV Powered 2800 inverters plotted against incident solar radiation using 5-minute data. Plot shows the efficiency of turning DC Power into AC Power on July 2007, at the AEC PV Test Facility.

4. PERFORMANCE OF INVERTERS

Inverters convert DC power from the PV array into AC power that is compatible with the utility grid. Inverter manufacturer's published data generally lists the efficiency of the conversion of DC power to AC power in the 92-95% range (see Figs. 3 and 4). These are efficiencies under optimal operating conditions for a system in which the array is properly sized for the inverter. Inverter manufacturers sometimes also quote an average efficiency that is more appropriate since inverters don't always operate at their nominal rating (e.g. Islam et al. [5]).

4.1 Characterizing inverter performance

Peak efficiencies are not maintained over the whole range of operation, but inverters generally operate at greater than 90% over much of the range. Examples of PV inverter efficiency are plotted for a Fronius 2500 and three PV Powered 2800 inverters in Figs. 3 and 4. The efficiency was determined by dividing the AC power output from the inverter by the DC power input to the inverter. For incident radiation below 200 to 300 Watt/m^2 the inverter efficiency begins to decline. When the incident solar radiation is between 50 and 100 Watts/m^2 the efficiency of converting DC to AC power falls off to around 70%. This is a considerable improvement over older inverters.

It is worthwhile to note that the inverter efficiency very slowly declines after peaking with incident energy levels around 400-700 Watts/m^2. This is partially related to the temperatures increases inside the inverter when it handles loads with more power.

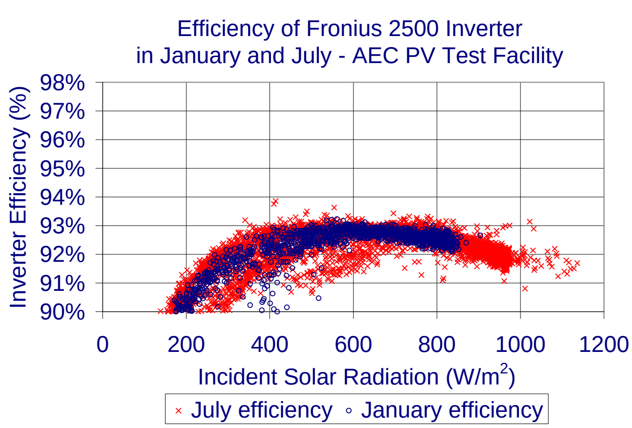

Fig. 5: Efficiency of the Fronius 2500 Inverter in January and July, 2007. Note that the efficiency is the same in either month. The inverter is located inside an unheated mechanical room.

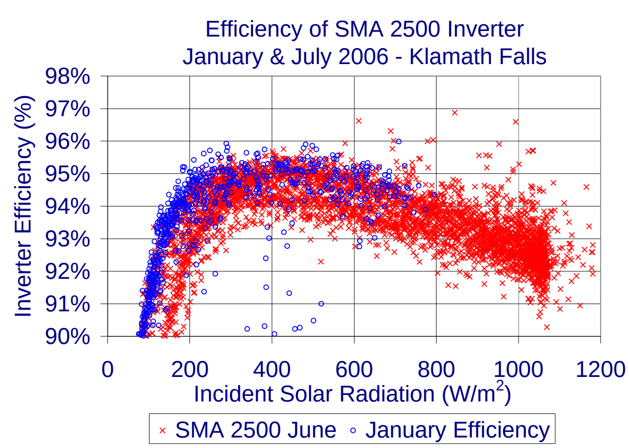

Fig. 6: Efficiency of SMA 2500 Inverter in January and June, 2006. Note that the efficiency of the inverter improves in January. The inverter is located outdoors.

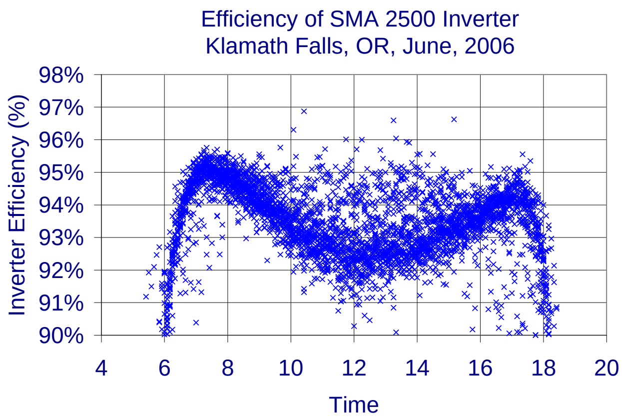

Fig. 7: Efficiency of an SMA 2500 inverter at Klamath Falls, Oregon in June. The data are from 5-minute averaged data.

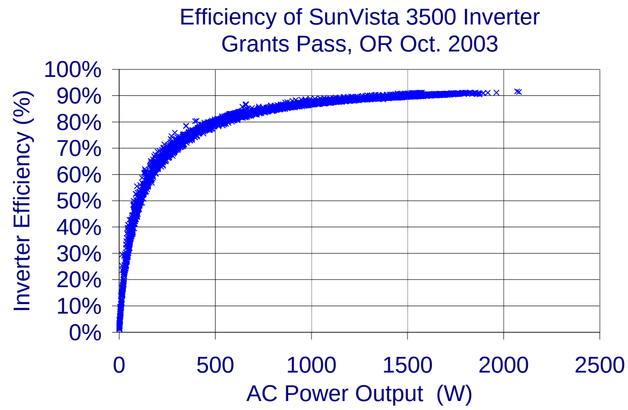

Fig. 8: SunVista 3500 inverter efficiency. Inverter combined three 1 kW arrays, one facing east, one south, and one west.

4.2 Effect of ambient temperature

To check for seasonal variations of the DC to AC conversion efficiency, the efficiency for January and July are plotted in Fig. 5 for the Fronius 2500 inverter at the AEC PV Test Facility. In general, the efficiency curves fall on top of one another and there is no affect of season visible. However, as shown in Fig. 1, the inverter is in a mechanical room under the roof and the temperature differences between winter and summer are not as drastic as they would be for inverters located outside.

In Fig. 6, January and June inverter efficiency data are compared an SMA 2500 inverter installed in Klamath Falls that is located outdoors. Fig. 6 shows that the efficiency of inverters located outside can change with season. The inverter's efficiency in a cold month of January appears to be slightly greater than the efficiency in June, a much warmer month.

If there is a small performance improvement in January compared to June related to temperature, this difference should also show up during the day when the morning temperatures are lower than the afternoon temperatures. Indeed, the highest inverter efficiency occurs during the morning hours (see Fig. 7). From Figs. 5 and 6, one can see that the peak efficiency occurs when the incident solar radiation is about 600 W/m^2. As the incident solar radiance increases, the inverter efficiency slowly decreases. Hence the 2-3% dip in efficiency during the middle of the day in Fig. 7 is related to the decrease in efficiency with increasing solar radiation above its optimum operating point.

To more clearly see the effects of temperature on inverter performance, it is necessary to make comparisons with similar irradiance ranges. Using June data from Klamath Falls, the average inverter efficiency was calculated for irradiance between 650 and 700 W/m^2 in the morning and the afternoon. In the morning, the average inverter efficiency is 94.4% and the average ambient temperature is 15.6 ºC. In the afternoon, the average efficiency is 93.5% and the average ambient temperature is 26.2 ºC. Assuming this is typical, then the inverter efficiency falls about 1% for about every 12 ºC rise in ambient temperature. This explains why the inverter efficiency is about 1% lower in the afternoon than the morning in Fig. 7.

4.3 Array size and inverter efficiency

An important design issue is to construct the PV system so that the inverter will be operating in its optimum range most of the time. However there are times when one would like to add a few more panels to an array or that conditions don't allow for the optimal number of panels to be installed. This leads to the following question: What happens if the system is undersized or oversized with respect to the inverter specifications?

The performance of a SunVista 3500 inverter is shown in Fig. 8. The inverter is powered by three 1 kW arrays, one facing east, one south, and one west. The SunVista inverter is designed to blend output for up to three different input strings, each with their different MPPT requirements. Only when the arrays are near maximum power production is the inverter efficiency above 90%. Because the arrays are facing different directions, the inverter is never operating near at its full capacity and the average DC to AC conversion is below 90%. Therefore the overall inverter efficiency would be greater if all three arrays created more power.

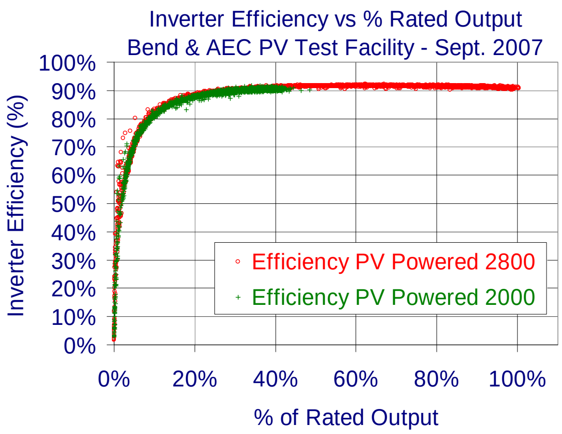

Fig. 9: Plot of inverter efficiency against rated output power for September 2007. Data for the PV Powered 2800 come from the AEC PV Test Facility. Data for the PV Powered 2000 come from a site in Bend. Note that the PV Powered 2800 and the PV Powered 2000 follow the same efficiency curve even though the PV system at the AEC PV Test Facility has 3600 W_{DC} in modules is occasionally over powered and the PV system in Bend is significantly underpowered and only has 1125 W_{DC} of modules.

In Bend, a PV Powered 2000 was installed on a 1.12 kW_{DC} PV system. This system is extremely undersized for the inverter. At the AEC PV Test Facility in Eugene, 3.6 kW_{DC} of modules were connected with a PV Power 2800 inverter. This was an attempt to see what happens when the array size is larger than the optimum for the inverter. Fig. 9 plots the inverter efficiency against the system output divided by the system rating.

The inverter efficiency is approximately the same for the two PV Powered inverters except that the Bend system never generates more than 50% of the rated output. On

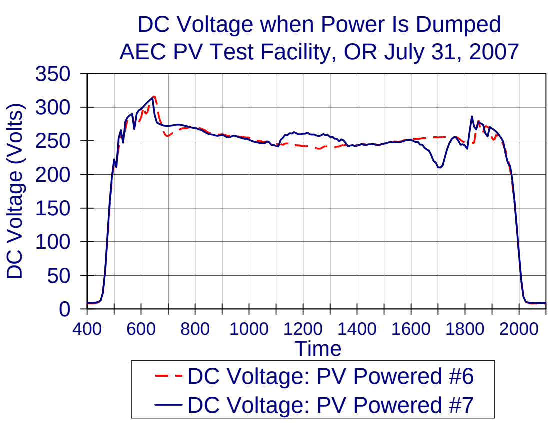

Fig. 11: Inverter moves off max power point by increasing DC voltage. PV Powered inverter #6 operates normally while PV Powered inverter #7 dumps power (increases DC voltage) to keep AC power from exceeding specifications.

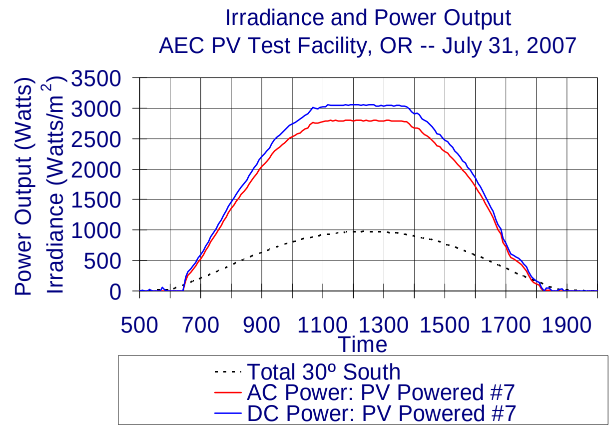

Fig. 10: Plot of DC and AC output of PV array connected to a PV Powered 2800 inverter. Note the maximum AC output is about 2800 watts. Also note that the DC power also plateaus.

average, the PV system in Bend will never be as efficient as the PV system at the AEC PV Test Facility because the PV system at best is operating in the 20 to 40% range of rated output and hence is operating in the 87 to 91% efficiency range during the sunniest periods.

Therefore, tests of inverter efficiency should be conducted with properly sized arrays. It also means that daily efficiencies will be weighted over the whole range and is not necessarily a reliable number on which to gauge the performance of an inverter.

Also, there can be a problem if the inverter is overpowered. Inverter manufacturers often include the maximum AC output in their names, like the SMA 2500 or the PV Powered 2800. The inverter ratings represent the

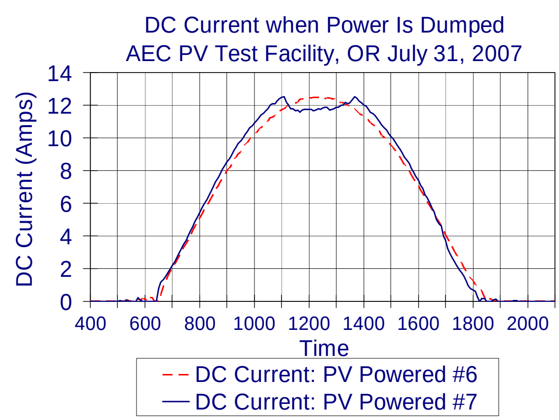

Fig. 12: Inverter moves off max power point by increasing DC voltage and hence decreasing current. PV Powered inverter #6 operates normally while PV Powered inverter #7 dumps power to keep AC power from exceeding specifications.

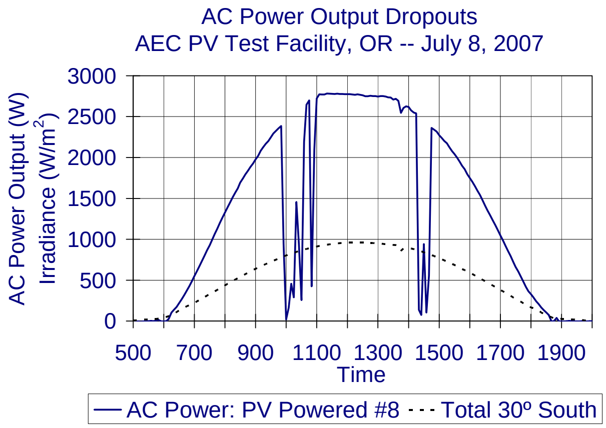

Fig. 13: Plot of power dropout on July 8, 2007 at the AEC PV Test Facility. Note that other inverters did not drop out and the problem is likely related to the calibration of sensors monitoring the utility power.

maximum AC output power from the array. Sometimes PV arrays are designed with an additional module that could cause the output to exceed design specification or incident solar radiation can occasionally exceed the 1000 W/m^2 standard used for the design. If excess power could be generated that would exceed the designated output limit, then the system has to shed that power so that it does not exceed its maximum specifications. These specifications are to protect the inverter or circuitry from being damaged.

To prevent the power rating to be exceeded, the inverter either decreases or increases the DC voltage so that the AC output power does not exceed the specifications. DC and AC power output plotted in Fig. 10 shows that the AC power specification of the PV Powered 2800 is not exceeded. This is typical of other inverters also. What happens is that the inverter moves off the max power point by increasing the DC voltage so that the AC power does not exceed 2800 watts.

Fig. 11 shows the DC voltage of two PV Powered 2800 inverters, one of which has enough panels to exceed the 2800 AC watt output limit. The max power point tracker makes an adjustment to increase the DC voltage slightly so that the AC power output does not exceed specifications. At the same time as the DC voltage is increased, the DC current is decreased (see Fig. 12), as expected (see the IV curve in Fig. 2).

Providing slightly more power to the inverter than the inverter's loaded nameplate value has not significantly affected the performance of the inverter over the three years of this study However, system designers should follow inverter specifications.

Software tools that estimate system performance are usually based on DC rating of the panels and do not take into account the energy lost if the PV arrays produce more power that the inverter is designed to handle. With hourly or shorter time predictions, periods when predicted performance exceeds inverter specifications can be lowered to maximum power allowed and thus more accurately reflect that actual performance.

More sophisticated estimation programs should have algorithms built for specific inverters. Generic PV performance models do not incorporate specific inverter performance curves, and in fact are based on the performance of older style inverters. Since most of the energy is produced when systems are operating with clear or nearly clear skies, the efficiencies are within a few percent of peak operating efficiency. By making slight changes, such as an inverter operating at 91% instead of 92% or vice versa, the overall performance of the system can be adequately estimated. However, some inverter manufacturers are beginning to supply software with their inverters to ensure more accurate performance estimates.

4.4 Grid related shutdowns

Inverters sense the utility frequency and voltage and will shut down if the inverter senses conditions outside the range expected for utility power. This feature of inverters is designed to prevent the PV system from feeding power back onto the grid when the grid goes down. For example, if a tree limb falls and breaks a power line, it would be unsafe for the PV system to power the line from the house side of the line.

Some of the older inverters had trouble restarting when the grid went down and had to be restarted manually. We have not seen this problem with new models of inverters. However, we have seen inverters shut down when the gird power is still available.

When the inverters shut down for short periods of times, it is often impossible to see without monitoring the inverter and having short interval data. A problem can occur if the inverter senses the voltage from the utility is outside specified levels. This is a design feature of grid connected inverters to ensure that the inverters are not dumping power onto the utility grid if the utility power goes down. However, if the inverter is not properly calibrated or if the utility voltage goes outside the specified limits, such shutdowns do occur. The data points that are far from the typical distribution in Figs. 3 and 4 are the result of the PV system shutting down when the system should be producing power.

The dropouts are illustrated in Fig. 13, a plot of 5-minute data from July 8, 2007. Dropouts take less that a second and typically last at least 5-minutes before the inverter tries to re-sync with the utility grid. The dropouts don't look sharp in 5-minute data plots because the dropouts rarely happen on the exact minute and some normal performance values are averaged in data when the problem starts or ends. Sometimes this problem can persist over hours, but shorter time intervals are more typical.

With very short time interval data, one can see that the power actually goes to zero within about a cycle and the inverter takes five minutes or more before it attempts to start operating again.

5. SUMMARY OF RESULTS

The article shows results from several inverters. The characteristics and issues discussed have occurred in several different brands and to some degree are generic with inverters.

The following assertions can be made:

In general, grid tied inverters convert DC power to AC power with an efficiency of 90% or more most of the time. Inverters can even work to some extent when irradiance levels are down to 40 or 50 Watts/m^2, but performance starts to drop off dramatically when irradiance levels reach the 100-200 W/m^2 level.

Inverters reach their maximum efficiency when they operate about 50% of the maximum rated output. Above their peak efficiency the performance drops off slowly and is only down about 1% at 80% of the maximum rated output. Between 10% and 20% of maximum rated output, the efficiency of the inverters starts to drop dramatically. This behavior is better in newer inverters than older inverters and fortunately most of the incident energy occurs when the solar radiation is above these levels.

The performance of inverters located indoors is not significantly affected by seasonal weather changes. Systems located outdoors perform slightly better in the colder winter temperatures than during the hot summer weather. A closer look in June showed that the inverter efficiency dropped approximately 1% for every 12 ºC increase in temperature. This is not significant, but it is worthwhile to mount the inverter where it can get a nice cooling breeze in the summer.

Photovoltaic systems that are oversized or undersized do not perform as well as properly sized systems. This is particularly true for undersized systems which operate in a region of the efficiency curve where inverters don't perform as well. For oversized arrays, it is probably not cost effective to add extra panels to an array if the total power is going to exceed the nameplate rating of the inverter, since the excess power will be dumped during the sunniest part of the year. Of more concern is the effect of the added stress that might be put on the inverter associated with excess inverter loading. So far, that hasn't seemed to be a problem.

A big concern is when inverters shut down when they falsely conclude that the grid power is down and it isn't. Some inverters seem to have this problem more than others even within the same model lines and when connected to the same utility line. This problem can go unnoticed as the system is working most of the time. The source of this problem can be that the utility grid voltage is operating too close to the edge of the range acceptable to the inverter.

Solutions to this problem can range from re-calibrating the inverter window, installing a different gauge of wire to reduce the voltage drop, or replacing an overloaded utility transformer that is unable to maintain voltage within the tolerances of utility specifications.

The solar market has now become large enough to attract a steady stream of new and improved inverters. Several of the inverters in this report are no longer being manufactured. New and improved models are on the market and inverter prices also are coming down. However, it is still important that the inverters perform reliably over time and be easy to maintain. Monitoring of new inverters is important to ensure that their quality and performance is maintained and that any problems that do occur are identified quickly.

6. ACKNOWLEDGEMENTS

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