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Performance Analysis of Grid-tied Sine-wave Inverters in a Hybrid Power System

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Abstract

The inverter performance model provides a new opportunity for accurately monitoring the performance and health of the inverter in real time. Grid-tied inverter monitoring can be accomplished by using a data acquisition system which provides a periodic measurement of dc voltage and power, as well as true ac power. In real time, inverter's efficiency can be calculated empirically and compared to the inverter efficiency determined using the inverter performance model. Deviations between measured and calculated inverter efficiency would provide direct evidence of inverter malfunction or degradation in performance. It is likely, given experience, that the nature of the deviations would provide the diagnostic information needed to define required inverter maintenance for optimum future performance.

Keywords: Performance model, Grid-tied Inverter monitoring, Data acquisition, Measured and calculated efficiency, Maintenance

1.0 Introduction

Photovoltaic generation is recognized as one of the most technical content and prospect of technology. Along with the development of global industrialization, human energy demand is increasing day by day.

In order to step up grid capacity or increase reliability of grid power supply other energy generation process differ from the conventional means of generating is now scientifically implemented through renewable energy source such as wind ,sun etc.

The combination of the various powers to achieve a single power output is referred to as hybrid power system. Hybrid power system has been implemented in different part of the world – case point in Taiwan and Ethiopia. The hybrid power system could be stand alone system or grid connected system depending on the purpose of implementation. The hybrid power system consists of various component and devices which make power generation possible. One of the major devices of a hybrid power system is the power inverter.

The inverter is a power electronics converting device that is used to maintain the flow of energy between dc and ac component. That is, it is used to convert d.c power into ac power. The attention of this paper is on pure sine wave inverter. The grid tied inverter can feedback energy into the distribution network because it produce alternating current with the same wave shape frequency as supplied by the distribution system automatically in the case when utility switch off. The energy converted can be used to operate ac equipments such as computer, television and radio receivers, machines, telecommunications etc.

This paper does not present result on the design and construction of power inverters. It focus on the performance of sine wave inverter thereby showing an analysis of the behavior of a sine wave inverter as a device employ in the power system for power conversion.

The inverter performance analysis can be use in conjunction with photovoltaic array performance model to calculate the expected system performance (energy production), to verify compatibility of inverter and PV array electrical characteristics and continuous monitoring of inverters performances characteristics that may indicate the need for repair and maintenance.

The inverter performance model requires a set of measured performance parameters (coefficient). This analysis does not provide electrical engineering model of the circuit characteristics or power conditioning algorithm used in the development of new inverters design, rather it is empirical or phenomenological analysis that simply but accurately replicate the power delivery characteristics of the (dc) to (ac) inversion process.

The manufacturer specification sheet provide the initial parameters, field measurement operations provide additional parameters and accuracy, and detailed performance measurement as conducted by testing laboratories provide further refined parameters.

A study of different literatures reveal that significant research is going on in various labs all over the world to improve the performance of on-grid inverters using different techniques. This paper will begin with a quick view of sine wave inverter as compared to other types of inverters and inverter efficiency and efficiency curve which will also be of useful help in the choice of inverter for use in a hybrid power system. Section 2.0 of this paper briefly discussed the literature review and innovative ideas. The evaluation of the Grid-tied inverter efficiency was explained in section 3.0. Section 4.0 narrates the inverter performance evaluation in hybrid power system. The models for evaluating inverter performance were clearly explained in section 5.0.The laboratory performance measurements, discussion and results were enumerated in sections 6.0 and 7.0 respectively. Finally, the conclusions were enumerated in section 8.0.

2.0 Literature Review and Innovative Ideas

The sine wave inverter is one of the major components of hybrid power system. Since the appliances to be powered by the energy generated from the hybrid system utilize alternating current (ac), The inverter perform the function of converting the direct current (dc) generated from the solar cell obtain from photovoltaic array into ac component. The review is outlined with following sub-topics:

Grid-tied Sine-Wave Inverter

The inverter employ in the hybrid power system is a sine wave inverter. Inverters are rated according to output wave form. Over the years the design of inverter has been on tremendous advancement to achieve inverter with better output waveform as such research is still on ongoing to improve the inverter technology. Of the different dc to ac inverter available, there are essentially two different form of ac output generated (Modified sine wave and pure sine wave). A modified sine wave can be seen as more of a square wave than a sine wave, it passes the high dc voltage for specified amount of time so that the average power and rms voltage are the same as if it were a sine wave. These types of inverter are much cheaper than sine wave inverter and therefore are attractive alternative.

Pure sine wave inverters on the other hand produce a sine wave output identical to the power coming out of an electrical outlet. The pure sine wave inverters are able to run more sensitive device than modified sine wave which may cause damage to such as: Laser printer, Laptop computer, power tools, Digital clock and medical equipments etc. This form of ac also reduces audible noise in device such as fluorescent light and run inductive load, like motors, faster and quieter due to low harmonic distortion.

The main building block of the power inverter are the oscillator and power amplifiers, these constitutes the various types of power inverter available and of course the various inverter design technique. This paper did not discuss the design analysis of the sine wave inverter, but laying emphasis on the basics to complement this research purpose.

Grid-Connected Inverter Control

The grid-connected inverter is important to couple the PV generator and utility system. It acts as the bridge to transfer the power that is produced from the PV cell to the utility. However, the inverter must produce good quality sine wave output, must follow the frequency and voltage of the grid. The inverter must observe the phase of the grid, and inverter output must be controlled both voltage and frequency variation. There are two categories of inverter control techniques, namely voltage and current control. Each type of control has a specific use. Voltage control is not employ for grid-connected inverter since the voltage on the output is generally dictated by the grid/utility power source. Instead current control is used to export a predetermined amount of current. With the effective value of the grid voltage being approximately constant to the corresponding predetermined level of power transferred to the grid. Not only will the inverter convert dc to ac power but it also regulates the PV system. The electronics that perform this task utilize special algorithm known as Maximum Power Point Tracking (MPPT) algorithm. The inverter affect the overall performance of the photovoltaic (PV) system and problem concerning inverter are difficult to notice unless it totally shutdown.

The grid-connected system comprise of PV array, the inverter device with the function of maximum power tracking and the control system.

Maximum Power Point Tracking (MPPT)

Solar inverter use power point tracking to get the maximum power from PV array, the solar cell have complex relationship between solar irradiation , temperature and total resistance that produce nonlinear output efficiency known as the I-V curve. It is the purpose of a MPPT system to sample the output of the cell and determine the resistance to obtain the maximum power for any given environmental conditions.

A typical solar panel converts only 30 to 40 percent of the incident solar radiation into electrical energy. Maximum Power Point Tracking is use to improve the efficiency of the solar panel. The inverter with the function of Maximum Power Point Tracking can inverse the electrical power into sinusoidal current and connect to the grid via a step-up transformer. The control system mainly controls the MPPT of photovoltaic, current wave form and power of the output of grid-connected inverter, which make the output of the grid corresponding with the export of the PV array. MPPT is not a mechanical tracking system that physically moves the module to make them point more directly at the sun. MPPT is a fully electronics system that varies the electrical operating point of the module so that the module are able to deliver maximum available power. The module power equals current times voltage. In a I-V curve, the dotted line is the dc. power (scaled to fit on plot) plotted for various voltages. The maximum point labeled and can be considered as the rectangle with the largest area that can be obtained using the current and voltage value, the curve is shown where the maximum power point is easily identified along with the open circuit voltage (V_{oc}) and short circuit current (I_{sc}). There are several MPPT algorithms available for this purpose and each manufacturer may apply any of them.

As the voltage increases or decreases from the Maximum Power Point, the power from array decreases as compared to the maximum power output possible, software or hardware in the inverter sense when the maximum power specification output of the inverter is about to be exceeded and instructions are sent to the Maximum Power Point Tracker to decreases the amount of power produced. The power inverter used 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 the specified range, the inverter will shot down immediately.

Typically an inverter can shut down for about 5-minutes if it senses abnormality. This is safety precaution but not only one that prevents inverter from sending power into the grid if the grid fails, inverter carry several anti islanding features that are of paramount important for safety reasons.

3.0 Grid-tied Inverter Efficiency Evaluation

The key risks or factors to consider when selecting an inverter for a utility- scale solar plant can be broadly defined as technology risk, performance risk and financial risk. It is important to carefully consider each of these risks in order to minimize adverse financial impact to utility-scale projects. Efficiency is easily the most common performance measure associated with PV inverters. Yet, there are several inverter attributes that can affect a conventional efficiency number. Inverter efficiency directly impacts the ability to maximize harvest, which is the ultimate goal. Inverter performance is closely tied to technology risk. In many ways, the technology platform is fundamentally tied to performance. Performance is the primary attribute that optimizes the financial returns of a PV plant, so it is essential to managing financial risk.

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.

By efficiency, we are really saying, what percentage of the power that goes into the inverter comes out as usable AC current (nothing is ever 100% efficient; there will always be some losses in the system). This efficiency figure will vary according to how much power is being used at the time, with the efficiency generally being greater when more power is used. Efficiency may vary from something just over 50% when a trickle of power is being used, to something over 90% when the output is approaching the inverters rated output. An inverter will use some power from your batteries even when you are not drawing any AC power from it. This results in the low efficiencies at low power levels.

The efficiency specified for the inverter is determined using a high precision measuring process and represents the ratio of the output power to the input power during nominal conditions. These specifications are also verified by independent testing institutes. Inverters not operated under nominal conditions, but rather under other conditions, such as with deviating input voltages, under partial load or at an increased ambient temperature produce deviating efficiency values.

If operators conduct an efficiency calculation themselves by measuring the current and voltage values at the input and output using commercially available measuring devices with larger tolerances, the results yielded cannot be used. The efficiency can only be precisely determined using high-precision and very expensive performance analyzers under laboratory conditions, which allow all input and output values to be measured simultaneously. Conversion efficiency of DC/AC inverters depends on some parameters and fluctuates over the input power of the inverter. Since the PV inverters operate under a fluctuating input power supplied by the PV modules, conversion efficiency must be measured against the weights of the probable power ranges which represent the various irradiation values. This approach of having different weights for different irradiation ranges resulted in two basic weighted conversion efficiency models of ηEURO and ηCEC. The two efficiencies involved in the inverters are conversion efficiency (ηconv) and MPPT efficiency (ηMPPT).

Grid-tied Inverter Efficiency Curve

Since the inverter is the brain box of a hybrid power system (grid-tied), it is important to know that inverter efficiency is not just a fixed number. Inverters have what is called an ‘efficiency curve’ usually displayed in a chart that shows how efficiency fluctuates with the output power or the voltage fed into it. Each brand and model of inverter has it own efficiency curve. Small losses are inevitable, but with a good inverter, greater amount of electricity ends up where you want it to or fed into the grid.

The inverter efficiency curve is a graph that describes how the inverter’s changes with the inverters’ power output (see figure 1 below). In choosing an inverter for the hybrid system or for any application, it is paramount to know the inverter ‘real-world efficiency’ instead of relying on the manufacturer specifications. The CEC or European Efficiency numbers are better for comparing PV inverters. To understand how the inverter will perform then the inverter’s ‘efficiency curve is important’.

The terms referring to efficiency when shopping around for inverter are: peak efficiency, Euro efficiency and see CEC efficiency.

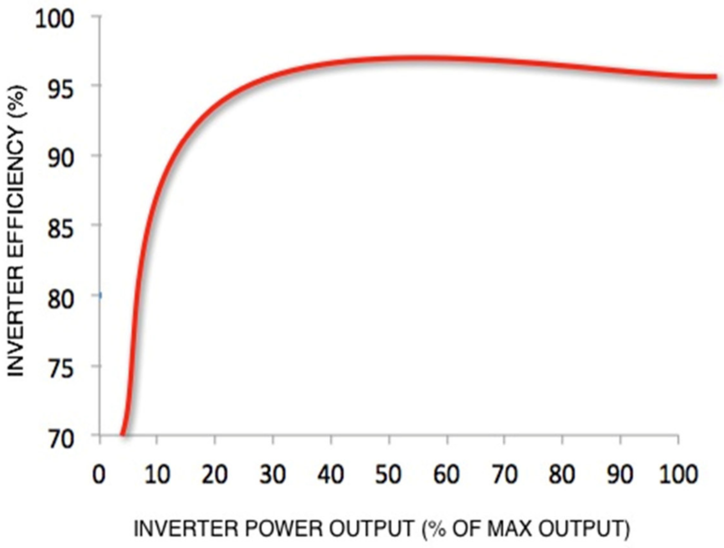

Figure 1: The Inverter Efficiency Curve

Peak Efficiency

The nominal rating for an inverter is usually its ‘peak efficiency’. It is calculated as DC input to AC output when the inverter is operating at its rated capacity. Peak efficiency for some of the best inverters can get up to 99%. Although this efficiency is high, the inverter may only work in peak efficiency range for a short part of the day or not at all. This implies that PV inverters peak efficiency is a measure of your inverter’s efficiency at a specific level of input power (watts). This is why the Euro and CEC weighted efficiencies have been developed. They recognized that inverters don’t always operate in optimal condition, and instead these measurements offer an indication of how an inverter might perform through out the day.

The figure 2 shows an efficiency curve where peak efficiency is about 250W.

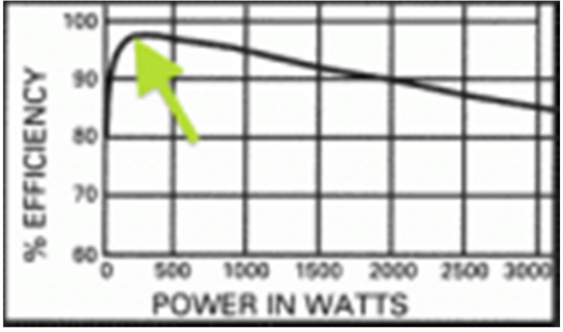

Figure 2: The Efficiency Curve

Euro and CEC Inverter Efficiency:

The Euro efficiency and CEC (California Energy Commission) efficiency are ‘weighted’ efficiencies. In calculating them, efficiency of an inverter at different spot within the operation range are taken into consideration and balance against each other depending on importance. These measures are generally more useful than peak efficiency because they measure inverters’ performance across the range of the inverter’s capacity. This gives a better idea about the inverter’s operating profile over the course of the day. Calculating weighted efficiency requires first selecting a few dc levels related to the inverter’s rated capacity. There are six efficiency points in the calculation as shown in the formulas below:

California Energy Commission (CEC) weighted efficiency

$$\eta_{CEC} = 0.04 . \eta_{10\%} + 0.05 . \eta_{20\%} + 0.12 . \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%}$$

European weighted efficiency

$$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.10 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.20 \cdot \eta_{100\%}$$

Where subscript xx% can be read as when operating at xx% of the rated capacity and the numbers multiplying the percentage are the weighting coefficients (adding up to ‘1’ for 100%).

The coefficients ‘weigh’ the importance of inverter output efficiency at different efficiency levels based on assumption (assumption based on observation and monitoring) about how often the inverter will perform at various level. The difference between CEC and the Euro efficiencies can be found in which levels are included and how the weights (%) at each level are determined.

Although both these efficiency ratings are great ‘at a glance, perspective on an inverter’s efficiency, the best thing to do is to look out for the inverter efficiency profile. This will give details on how the inverter will perform in an area’s climatic conditions with the system array at different out put level. This will enable you to more accurately understand how your inverter performs.

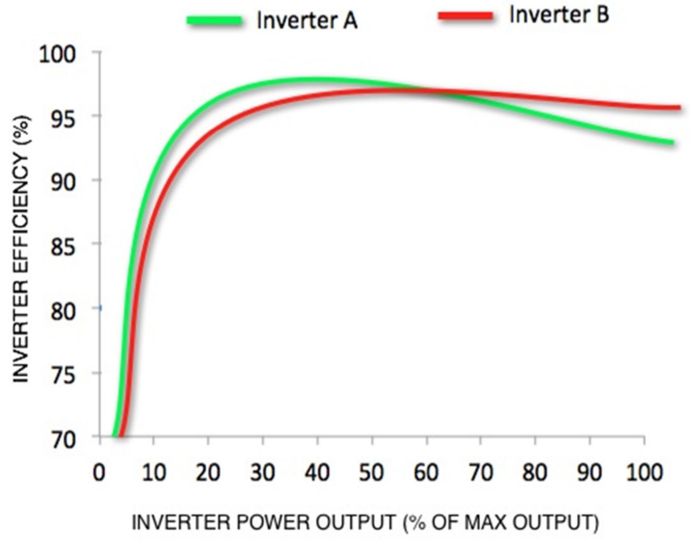

Figure 3: Inverters Efficiencies Comparison

The reason for the curve is to ensure that the PV panels are not operating on the worst part of the curve. If the inverter regularly operates below 20% of its rated power the efficiency is down the toilet.

Another quick reason is to be sure that the inverter with the highest max efficiency really is the most efficient. Such inverter will perform better than one with slightly lower efficiency. Take two inverters A and B as shown in the figure 3. For example, the inverter B has the highest max efficiency and as such will perform better as it has a higher efficiency over a broader range of power output.

Inverter Power Rating

Grid-tied inverters are most commonly rated by their continuous output (ac) power capability—the watts the inverter can output continuously. In the *National Electrical Code (NEC)*, a continuous load is defined as “a load where the maximum is expected to continue for 3 hours or more.” All circuits associated with grid-tied PV systems, on both the AC and DC sides of the inverter, are considered continuous. This continuous power output rating dictates the PV array’s maximum power value. Grid-tied inverters will limit their power output—if you design an array that supplies more power than the inverter’s maximum, the inverter won’t be able to process all the power. Instead, the inverter will waste any excess power as heat. As is the case with all electronics, generating unnecessary heat may reduce the inverter’s life.

Deciding on how large a PV array to connect to the inverter requires predicting output over the course of a year. Generally, PV arrays produce less than their STC (Standard Test Condition) rating, due mostly to conditions that differ from STC—like higher cell temperatures, lower irradiance, and module soiling. When predictable system losses are taken into account, a PV system owner can expect their array to operate at around 80% of the STC rating. Since these losses are consistently present, the size of the PV array can be designed to exceed the inverter's power rating.

Causes of Grid-tied Inverter Failure in Hybrid Power System

Inverters are considered the brain of the PV system and considered an expensive and complex element in the system. Field experience has shown that the inverter is the most vulnerable component. An investigation was carried out on 126 systems that provided 190 failure events, and results show that inverters dominate the outage causes of PV plants by 76%. Another survey reported is depicted that inverters are the leading cause of PV systems failure. The same conclusion is reported in, that states that 65% of outages of 213 events for 103 PV systems were due to inverters. The inverter failures can be classified into three major categories: manufacturing and inadequate design problems, control problems and electrical components failures. A study in Botswana reported that both tropical operating conditions and lightening effects cause 77% of inverter failures. Thermal management and heat extraction mechanisms of switching components and capacitors are considered one of the design and manufacturing flaws problems in inverters. Control problems are related to the interaction between the inverter and the grid, at the AC side, and between the inverter and the PV array, on the DC side. The components of PV inverters are exposed to electrical and thermal stresses during their operation. Consider the electrolytic capacitors as the most particularly troublesome component, and focused on IGBT (Insulated-Gated Bipolar Transistor) as the leading component in the failure of PV inverters.

4.0 Inverter Performance Evaluation in Hybrid Power System

Electricity generation of a PV power system depends on the solar irradiation received by the PV modules and the efficiency of the system. The efficiency of a PVPS (Photovoltaic Power System) on the other hand, is a multifold concept covering conversion efficiency of the PV modules along with the conversion efficiency, MPPT performance and some other properties of PV inverter used. PV inverters are evaluated with their overall efficiency. Overall efficiency is described as the ratio of the energy delivered by the PV inverter at the AC terminals to the energy provided by the PV array.

The inverter is equipped with measuring devices that ensure proper system management. The inverter's task is to determine the operating point along with the maximum yield, while a counter is to take a precise energy measurement. Therefore, to achieve maximum energy conversion, it is crucial for the inverter to precisely detect changes in parameters, such as grid current or PV voltage. In this case, high reproducibility is more important than high absolute accuracy. Compared to the calibrated feed-in counter, the inverter's measuring channels may have a tolerance of up to ±3% based on the respective final value of the measurement range under nominal conditions. If the feed-in power is low, the relative deviation may therefore also be correspondingly larger. These deviations also then recur proportionately in the derived measurements, such as the feed energy. In addition, line from the AC cabling must also be added. These losses, as recommended in the device documentation, must not exceed approx. 1% at nominal power. In case of doubt, check whether the installed AC cabling matches the cable lengths and the corresponding cable cross-sections recommended in the device documentation.

Deviations and Malfunctions Records in Grid-tied Inverters

Taking into account the aforementioned measurement tolerances and influencing factors, the sum of the tolerances of the measuring devices may allow deviations between an inverter display and the feed-in counter to occur. Since the tolerance range for these deviations particularly depends on the present feed-in power, a maximum permissible deviation cannot be specified. However, a deviation of more than 10% under rated operating conditions indicates a malfunction with one of the measuring devices. In this case, the entire system should be precisely examined.

Calculation example in percentage of error information and the absolute value:

Current sensor measurement range (final scale value):
50 A, permissible error ± 2 % (equals absolute value of ± 1 A)
Permissible values for a current of 20A: 19A … 21A (equals relative value of ± 5%)
Permissible values for a current of 2A: 1A ……. 3A (equals relative value of ± 50%)

Inverter manufacturer's published data generally lists the efficiency of the conversion of dc power to ac power in the 92-95% range. 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. The inverter performance efficiency will depend on two minor factors and one major factor.

The minor factors are:

- The ambient temperature of the inverter: The hotter the inverter gets, the lower its performance efficiency will fall. This is why it should always be installed in a shade which is well ventilated.
- The dc voltage going into the solar panel (this is quiet technical to explain in this paper).

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.

Inverter Reliability Standardization

Inverter reliability is often regarded as the most likely contributor to performance failure in a typical utility-scale photovoltaic plant. Literature has revealed at different inverter manufacturers have different opinion about reliability of inverter and the possibility to standardize.

Photovoltaic (PV) systems are installed all around the world to produce electricity from solar energy. The evaluation of its long term reliability is fundamental for PV system and it should include both a complete and partial outage of the system. There's been a movement in the solar module industry to improve module reliability. But while solar inverter interconnection and safety standards exist, there are no well-established *reliability standards.* In fact a system working at a level below expectations can be considered in partial outage. For example, a small power loss due to damaged single cell can be considered a failure in PV system.

In literature several papers consider the reliability of PV components and in particular that of PV modules. A fewer number of publications considered the failures of the overall PV system. In a failure analysis shows that inverters, AC subsystems, support structure DC subsystems and modules contribute in 43%, 14%, 6%, 2% of PV system failures respectively. There are different opinions by various individuals concerning Inverters reliability and standardization. Few of such opinions are related here:

"Reliability is critical in the inverter industry. If an inverter has poor quality and reliability issues, it won't last for long in the demanding U.S. market." (*Thomas Enzendorfer, Director, Solar Energy Division, Fronius USA*) "Ideally there should be inverter reliability standards considering that inverter is a critical component of a solar system. However, unlike performance data, it is very difficult to set reliability standards and more difficult to measure because the reliability data should be gathered in the field over a long period of time." (*Susanna Huang, Ginlong Technologies*).

"It is very difficult to standardize reliability for inverters because there is not the same set of standards around test conditions. Inverters are far more differentiated than modules, and the variation in rating and application for critical variables like temperature, power factor, DC voltage range and AC voltage, as well as grid quality, can significantly affect the reliability of an inverter. That said, it is critical that there is more transparency and standardization of inverter reliability data, because as the industry matures, developers need to access new forms of financing that require more standardization."

(*Tucker Ruberti, Director of strategic marketing, Advanced Energy*). "A blanket standard is not needed, but proving high reliability is a great weapon for competitive advantage. There are many ways to increase reliability confidence in the design process, but we have found that actual field and lab toughness testing is most effective."

(*Ed Heacox, Chint Power Systems)* "Reliability can be measured by mean time before failure (MTBF), but more importantly, there is the question of mean time to repair (MTTR). While a component failure is a relatively rare event, if it takes hours or days of downtime to repair, productivity will suffer. Therefore it is advantageous to use a design with as much modularity as possible, allowing repairs to be done rapidly and efficiently."(*Lou Lambruschi, marketing services and E-business manager at Parker Hannifin*}

Reliability is designed into inverters from the start by eliminating components that are prone to failure, and by using conservative design margins. As part of internal testing, there should be various reliability tests, including thermal cycling and HALT testing."

Hybrid System Grid Related Inverter Shutdown

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. Providing slightly more power to the inverter than the inverter's loaded nameplate value has not significantly affected the performance. 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.

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.

5.0 Models for Evaluating Inverter Performance

Manufacturers' specification sheets contain a variety of information essential to the successful application of a PV inverter, including ac voltage, ac frequency, maximum ac power and current, acceptable dc voltage range, maximum dc power and current, dc startup voltage, total harmonic distortion, power factor, and acceptable environmental extremes, as well as mechanical characteristics. However, the inverter's "power conversion performance" or efficiency is often provided as a single peak efficiency value, which can be misleading, and sometimes as a "California Energy Commission (CEC) weighted" efficiency value. Regardless, PV system engineers and analysts would benefit from more detailed performance characteristics.

Independent testing laboratories now provide more detailed inverter performance data, notably those laboratories supporting the solar power initiatives of the CEC. These laboratories typically use an inverter testing methodology based on the protocol collaboratively developed by Sandia National Laboratories and BEW. The objective of the CEC testing protocol is to verify inverter performance specifications, as well as to quantify performance characteristics as a function of power level and dc input voltage, the two parameters determined by laboratory evaluations to have the most significant impact on efficiency. The inverter test data documented by the CEC are thorough, providing measurements at six power levels and three different dc voltage levels. Five to seven replicate measurements at each condition provide good statistical rigor. Figure 1 illustrates an example of inverter performance data documented by the CEC, providing inverter efficiency (ac-power divided by dc-power) as a function of the ac-power output of the inverter, at three different dc voltage levels. Our effort, documented in this report, shows that by presenting the CEC test data differently, additional information can be obtained that is more directly applicable in modeling PV system energy production. Later in this document, several examples will more clearly illustrate the alternative procedure for extracting more information from the CEC data.

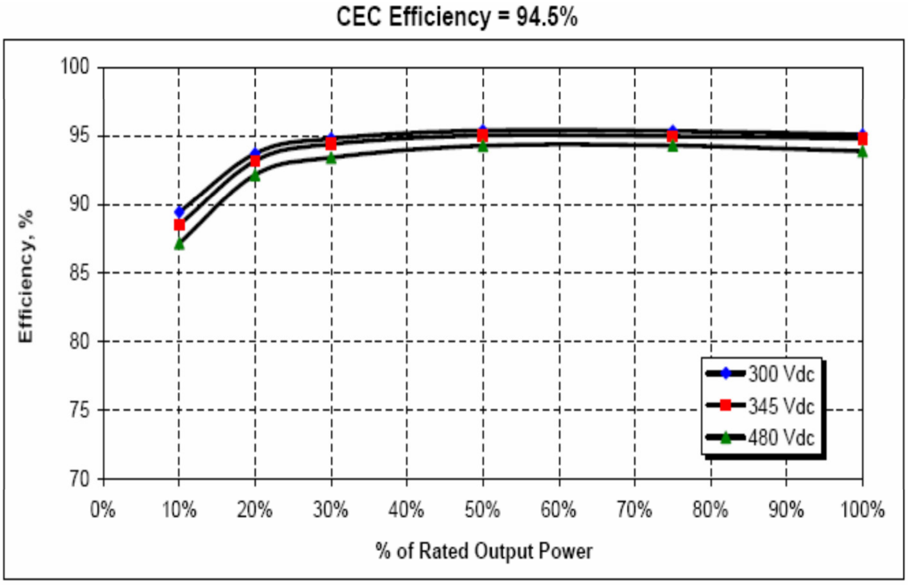

Figure 4: Inverter performance measurements conducted by a nationally recognized testing laboratory and documented by the CEC.

Inverter Performance Model Equations

The following equations define the model used to relate the inverter's ac-power output to both the dc-power and the dc-voltage, which were used as the independent variables. The parameters with the "o" subscript are constant values that define a reference or nominal operating condition.

The basic equations describing the model and the definition of all parameters follow.

$Pac = \{(Paco / (A - B)) - C \cdot (A - B)\} - \{(Pdc- B) + C \cdot (Pdc - B)\ 2\}$ (1)

Where:

$A = Pdco - \{1 + C1 \cdot (Vdc - Vdco)\}$ (2)

$B = Pso - \{1 + C2 \cdot (Vdc - Vdco)\}$ (3)

$C = Co - \{1 + C3 \cdot (Vdc - Vdco)\}$ (4)

Definition of parameters

Pac = ac-power output from inverter based on input power and voltage, (W)

Pdc = dc-power input to inverter, typically assumed to be equal to the PV array maximum power (W).

Vd = dc-voltage input, typically assumed to be equal to the PV array maximum power voltage (V).

Paco = maximum ac-power "rating" for inverter at reference or nominal operating condition, assumed to be an upper limit value (W)

Pdco = dc-power level at which the ac-power rating is achieved at the reference operating condition (W).

Vdco = dc-voltage level at which the ac-power rating is achieved at the reference operating condition (V).

Pso = dc-power required to start the inversion process, or self-consumption by inverter, strongly influences inverter efficiency at low power levels (W).

Pnt = ac-power consumed by inverter at night (night tare) to maintain circuitry required to sense PV array voltage (W).

Co = parameter defining the curvature (parabolic) of the relationship between ac-power and dc-power at the reference operating condition, default value of zero gives a linear relationship, (1/W)

C1 = empirical coefficient allowing Pdco to vary linearly with dc-voltage input, default value is zero, (1/V)

C2 = empirical coefficient allowing Pso to vary linearly with dc-voltage input, default value is zero, (1/V)

C3 = empirical coefficient allowing Co to vary linearly with dc-voltage input, default value is zero, (1/V)

Determination of Inverter Performance Parameters

The accuracy and versatility of the inverter performance model depends on the data available for determining the performance parameters used in the model. We structure our model to make it possible to add parameters successively, improving accuracy, as more detailed test data are available. Initial (default) parameters can be obtained from manufacturer specification sheets. If available, daylong ac-power and dc-power measurements from operating systems provide additional parameters and improved accuracy. Finally, detailed laboratory measurements, like those conducted by nationally recognized testing laboratories for the CEC, can be used to obtain all performance parameters currently included in the model. During the validation of our performance model, an initial database of inverter parameters was generated and is given in the appendix of this document. Using the methods described in this document, field measurements or tabulated performance data provided by recognized laboratories provide the means for adding parameters for new inverters to the database.

Manufacturer's Specification Sheets

The terminology used and the performance parameters available from manufacturers' specification sheets vary greatly. However, it is usually possible to determine reasonable estimates for the three parameters needed to provide a simple linear model for inverter performance (Paco, Pdco, Pso), with no dependence on dc-voltage input. The rated ac-power (Paco) is usually specified, as is the peak and/or CEC weighted efficiency. Dividing Paco by the efficiency value provides a value for the associated dc-power level (Pdco). The dc-power required to start the inversion process (Pso) may not be given in the specification, and should not be confused with the nighttime ac-power consumption (Pnt). Lacking a specification, a reasonable estimate for Pso is 1% of the inverter's rated power. Field and laboratory test data have indicated that the startup or self-consumption power, as used in our model, is typically larger than the power level sometimes referred to as "standby" power or "consumption during operation."

Field Performance Measurements

When accurate daylong measurements of both dc-power input and true ac-power (not volt-amps, VA) from the inverter are available, then additional performance parameters can be determined, providing improved accuracy for the inverter performance model relative to the simple linear model. Figure 4 illustrates field measurements of true ac-power, dc-power, and inverter efficiency over a 13-day period including both clear and cloudy weather conditions. The data values recorded were near instantaneous measurements, as opposed to average values determined over a time interval. The associated dc-voltage was also recorded during the field measurements. A parabolic fit (2nd order polynomial) to the measured ac-power versus dc-power provided parameters (Pdco, Pso, Co) used in the performance model. Paco was assumed equal to them manufacturer's peak ac-power rating. The quadratic formula was used to solve for both the x intercept (Pso) when Pac = 0 and for Pdco when Pac = Paco (2500W in this case). A chart of measured dc-voltage versus measured dc-power over the 13-day period was used to obtain an estimate for the Vdco associated with the peak power condition at Pdco, Paco. Good day-to-day repeatability in performance characteristics has been observed for a variety of inverters during field testing at Sandia; therefore, it is likely that measurements recorded over a single day would provide inverter performance parameters that are representative of expected behavior.

6.0 Laboratory Performance Measurements

In this case, the inverter had a reasonably large operational range for dc-voltage input; as a result, the inverter efficiency varied noticeably, being higher at low dc-voltage input.

The CEC test protocol provides inverter performance (efficiency) measurements at six different power levels (10%, 20%, 30%, 50%, 75%, and 100% of ac-power rating) and three different input voltage levels (V_{min}, V_{nom}, V_{max}). The mid-range dc voltage, $V_{nom,}$ defined by the CEC protocol (selected by the manufacturer at any point between V_{min} + 0.25*(V_{max}-V_{min}) and Vmin+0.75*(V_{max}-V_{min})), was used as the reference voltage, V_{dco}, in the inverter performance model. The CEC measurement procedure provides five to seven replicated measurements at each test condition, providing good statistical rigor. The primary limitation of the CEC procedure was that measurements were performed for a single inverter of each type; the inverter may or may not be representative of the “typical” inverter off the production line.

All the performance parameters required in the more complex inverter model, defined in Equations 1 through to 4 can be determined using the CEC test data. The procedure for determining performance parameters from the tabulated CEC data is the same as previously discussed for the case using field measurements. The distinction is that data at each of the three dc-voltage levels were treated separately, allowing three of the parameters (Pdco, Pso, Co) to be expressed as a linear function of the dc-voltage, Vdc, as indicated in Equations 2 through 4. Three separate parabolic fits were used, one for each set of ac-power versus dc-power measurements recorded at a near constant dc-voltage level. During analysis, the tabulated CEC test data were first combined using all replicate measurements, and then sorted by ascending dc voltage to combine measurements for each of the three common dc-voltage levels. The mid-voltage data, V_{nom}, provided the “reference” operating condition. In order to determine the coefficients C1, C2, and C3, the values for Pdco, Pso, and Co determined from the three separate parabolic fits were used to calculate the dc-voltage dependence for each factor. Graphs with linear fits to used are used o determine the coefficient C2, as well as the value for Pso at the V_{nom} reference voltage. The data for this inverter, as well as several others investigated, suggested that the dc-power required to start the inversion process was somewhat lower at the low dc-voltage level, consistent with achieving higher inverter efficiency at low dc- voltage levels. The same analytical procedure (linear fit) was used to determine C_1, P_{dco}, and C_3, C_o at the V_{nom} reference voltage.

7.0 Discussion and Results

The inverter performance model presented in this document improves the accuracy and versatility of models used for designing PV systems; in particular, assessments of ac energy production are more accurate. The performance model, along with additional parameters included in the inverter database, provides the information needed to ensure compatibility and optimum performance of arrays and inverters. The inverter model also makes it possible to monitor the long-term performance and aging characteristics of both inverters and systems with accuracy previously unavailable.

In order to make best use of the inverter model and associated database of performance parameters, the PV array performance model must provide calculated values for array open-circuit voltage (V_{oc}), maximum-power voltage (V_{mp}), maximum-power current (Imp), as well as maximum power (P_{mp}). The V_{mp} and P_{mp} values are used directly in the inverter performance model to determine ac-power production. By using hourly solar resource and weather data in the PV array performance model, several system design criteria can be evaluated. The calculated values for V_{oc}, V_{mp}, I_{mp}, and P_{mp} should be used to verify that the array Voc does not exceed the inverter’s maximum dc voltage (Vdc_{max}), the array Imp does not exceed the inverter’s maximum dc current (Idc_{max}), and that the calculated P_{mp} rarely exceeds the inverter’s peak dc power rating (Pdc_o).

The curve in fig. 5 shows that inverter efficiency is highest for dc voltages near the low MPPT limit and for array maximum power that only occasionally exceeds the inverter’s upper dc-power limit, resulting in an overall annual system ac efficiency of 15.5%. However, most system designers would opt to design the system a little more conservatively (i.e. 9 series by 2 parallel configuration), which raises the system voltage and gives more margin for wiring losses and long-term module performance degradation. The point of this discussion is that coupling an array performance model with the inverter performance model improves the ability to design and optimize PV systems based on annual ac energy production.

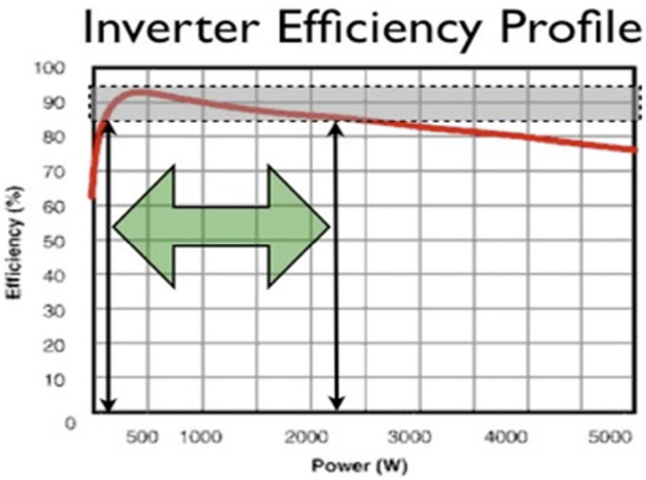

Figure 5: The Inverter Efficiency Profile

8.0 Conclusions

Providing slightly more to power to the inverter than the inverter's loaded nameplate value has not significantly affected the performance of the inverter. 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 than the inverter is designed to handle. With hourly or short time predictions, periods when predicted performance exceeds inverter specifications can be lowered to maximum power allowed and thus more accurately reflects that actual performance. Advanced inverter designs should have the inverter model incorporated in firmware, and should be equipped with accurate dc and ac power meters, as well as standardized communication protocol. These advanced features would provide direct inverter performance monitoring capability, help reduce the installation cost of PV systems, and facilitate expedient and cost effective field maintenance. Conceivably the PV array performance model could also be incorporated in the inverter's firmware providing system monitoring and diagnostic functions for the entire system.

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

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