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# Influence of irradiance, ambient conditions and AC power output on micro inverter temperature-overview

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*Solar energy is one of the cleanest and reliable sources of renewable energy on earth. Conventionally, extraction of solar power for electricity generation was limited to PV farms, however lately distributed generation form of solar power has emerged in the form of residential and commercial Grid Tied micro-inverters. Micro inverters temperature is strongly correlated with ambient temperature and PV module temperature, and moderately correlated with irradiance and AC power. Ambient temperature is the influencing factor under conditions of low irradiance in morning hours, when the irradiance is below 60 W/m$^2$. Noon time data analysis reveals that the micro inverters thermal behaviour is more strongly influenced by PV module temperature than AC power. In this paper review about electrical circuit topology and Influence of irradiance, AC power, ambient temperature on PV module and micro inverter are discussed.*

***Keywords:*** *PV module, MPPT, dual-axis, irradiance, CTP, DC-DC converter.*

## 1.0 INTRODUCTION

One of the major concerns for the future of the PV industry is the reliability of the PV system, inclusive of PV modules, interconnects, the inverter system, the grid connection and the mounting systems. Modern commercial PV module manufacturers typically provide a 25-year warranty and claim 1% power degradation per year. PV cells are semiconductor based electrical devices that can convert sunlight to electricity by using the photovoltaic effect. Today the market is dominated by crystalline silicon modules. These modules are mechanically robust enough to come with a 25 year limited warranty and a guarantee of 1% power degradation per year. Crystalline silicon modules can be categorized into mono-crystalline and polycrystalline, also referred as multi-crystalline, silicon type cells. They consist of front surface glass, encapsulant, 60 to 72 interconnected PV cells, a back sheet and a metal frame. The common front surface glass is a low cost transparent, tempered low iron glass with self-cleaning properties. This type of glass is strong, stable under Ultra Violet (UV) radiation and water and gas impervious. Ethylene Vinyl Acetate (EVA) is commonly used as encapsulant material. It helps to keep the whole module bonded together. EVA is optically transparent and stable under high temperature and UV radiation. Recent rapid growth of PV systems can be attributed to significantly reduced installation cost of the PV system in recent years. However, the total PV system price and installation cost were also reduced but at a much slower rate than the PV module price reduction rate alone. However, a system is only as good as its weakest link, and the reliability of the inverter system

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in particular is of high concern [2, 3]. Although limited studies have been conducted to date, an understanding of inverter thermal characteristics and behavior would provide critical insight to associated reliability issues. Therefore, the focus of this paper is to analyze the characteristics of a PV power plant to provide insight to the thermal behavior of a specific class of inverters: micro inverters.

### 1.1 PV System

A complete PV system consists of several sub-systems. The first subsystem is for power generation, consisting of: PV cells, modules and arrays. PV arrays are created by interconnecting a large number of PV modules with each other. The second sub-system is interconnecting and PV wire system. Depending upon the inverter system, interconnect can in series or parallel. The final subsystem is the PV inverter system. The output of a PV module or array is Direct Current (DC) power. Therefore, in order to connect to the grid or directly to common household appliances, the DC power must be converted to utility frequency Alternating Current (AC) power. This power conversion is completed via a PV inverter system. Currently, two types of inverter systems are used in PV systems: string inverters and micro inverters, as depicted in Figure 1.

### 1.2 Thermal Model for PV System

PV module temperature is influenced by irradiance, ambient temperature, power output,module material and associated heat transfer coefficients, including radiation and convection due to the wind. Many researchers have developed models to examine the thermal behavior of PV modules using an energy balance of convection, conduction,and radiation heat transfer along with a heat generation term arising from extraneous heat occurrences from power output inefficiencies [18–26]. The wind flow over the PV modules is turbulent, with particularly unpredictable fluid flow effects occurring near the roof edges, PV module edges or at the location of other obstructions.

## 2.0 INVERTER SYSTEM

Even though the working principle and topology is similar in both string inverters and micro inverters, there are significant differences between them interconnect systems and PV system output efficiency. In string inverters, a number of PV modules, electrically in series with each other, are connected together and the cumulative total DC power generated by the connected PV modules is supplied to the string inverter shown in Figure 1.

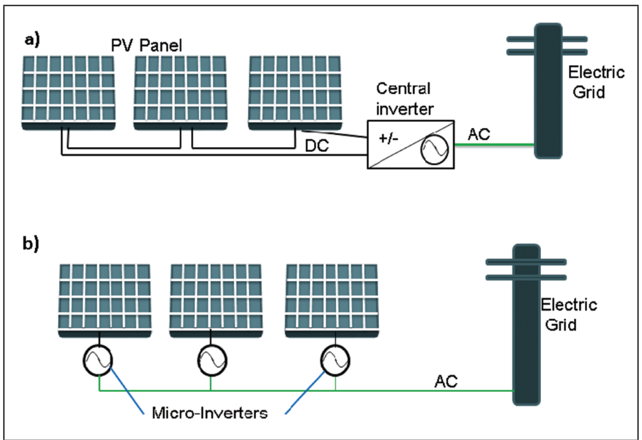


FIG. 1 STRING AND MICRO INVERTERS

The typical size of string inverters varies from 1 KW to 250 KW. Generally string inverters show high conversion efficiency, robust design capability and a low cost per watt. However, the current of all PV modules in an array connected to the string inverters is governed by the lowest current module as a result of the series connection. Consequently, maximum output cannot be guaranteed. Shading of one or more PV modules within the array, and the resulting power mismatch between the PV modules can lead to this situation. Particularly, shading is a very concerning issue as it can force other unshaded modules to operate away from their optimal Maximum Power Point Tracking (MPPT), creating a hotspot in the shaded module, leading either to cracking or damage. In some extreme cases, this can lead to fire. The other disadvantages with string inverter system are: a lack of module level monitoring, the required use of a high voltage line and the potential for a single point of failure. In a micro inverter system, a single micro inverter is dedicated to one PV module, and the AC output from different micro inverters of an array are in a parallel connection with each other Figure 1b. The typical size of micro inverters varies from 190 W to 300 W. There are several advantages of micro inverters over traditional string inverters. Each micro inverter is available to only one PV module, resulting in an optimized output from each module using panel level MPPT. Every PV module is connected in parallel with each other so shading, or a defective panel does not reduce the performance of the whole array. The micro inverter is free from a potential power mismatch, which gives design flexibility so that one can create an array with different power rating without losing performance. Micro inverters are incorporated with panel level monitoring, and as a result, a module failure can be detected instantaneously and remotely. Furthermore, the use of a low voltage DC line increases safety. The disadvantages of micro inverters include: a higher cost, lower efficiency compared to string inverters and a greater complexity of installation.

### 2.1 Micro inverter History and Evolution

Ascension Technology first developed the micro inverter in 1991 in the USA. However, under real-world outdoor conditions, a large number of failures were reported within eighteen months of installation [13]. Due to their poor reliability, cost and efficiency, first generation micro inverters could not compete against traditional string inverters. Motivated by the opportunity present in the residential market, Enphase Energy, founded in 2006, released their first micro inverter product in 2008. By 2013, they introduced their fourth generation micro inverter. Enphase offers either a 15 or 25-year warranty on their micro inverters.

### 2.2 Micro inverter Topology

A simple one stage micro inverter topology is shown in Figure 2, The total circuit can be divided into two sections: high and low frequency zones. The high frequency zone is also known as the resonant inverter zone. The DC power from the PV module is fed into the high frequency side of the micro inverter. The current flow towards the transformer is controlled by the high frequency MOSFET switches. The transformer converts the low voltage input to the high voltage sinusoidal waveform output at the switching frequency. This zone converts the high frequency power waveform generated from the resonant inverter to the much smaller line frequency waveform by using high voltage MOSFETs. Capacitors act as storage of the input power and filter out the input ripple to supply a constant current. Generally, [1-12] (depending upon topology) transformers are used to match the grid voltage.

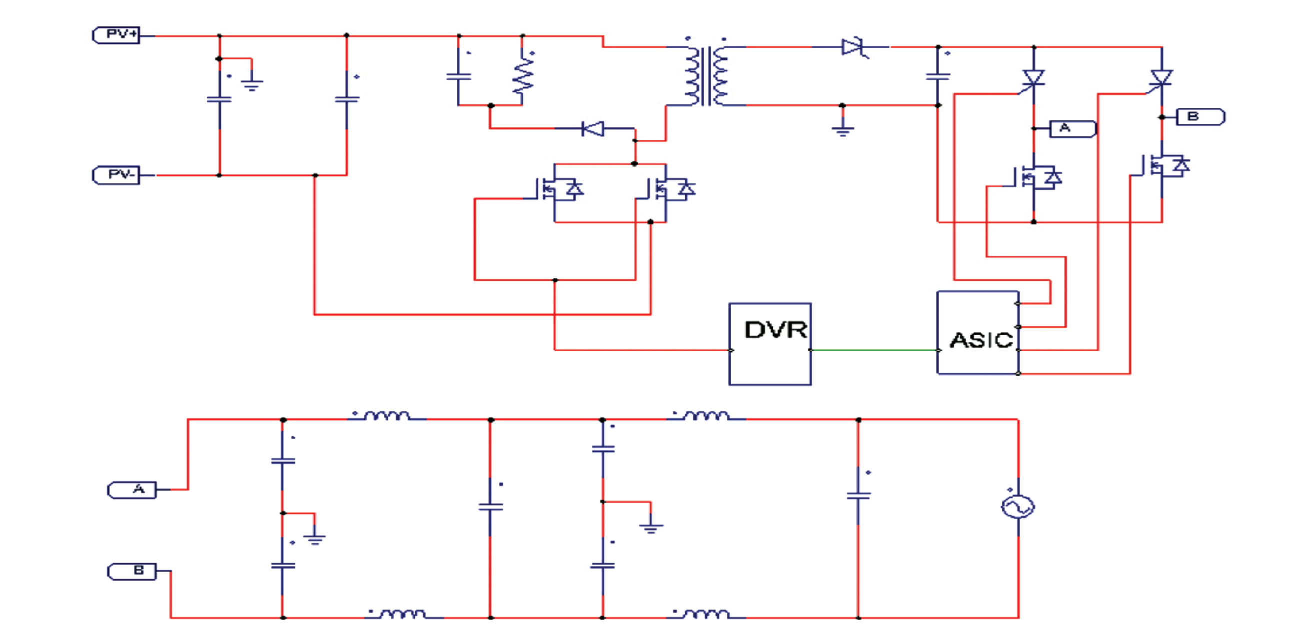


FIG. 2 CIRCUIT DIAGRAM OF SINGLE STAGE MICROINVERTER

## 3.0 CRITICAL TO LIFETIME PERFORMANCE (CLP) COMPONENTS

MOSFETs and capacitors are considered critical components (Table 1) of microinverters [18, 21]. The lifetime of the electrolytic capacitor is very much dependent upon the operation environment, and high operating temperature evaporates the aqueous component electrolytes, leading to an increase in equivalent series resistance (ESR). This introduces more dissipative heat inside the capacitors which in turn accelerates the evaporation rate and reduces the capacitance. Since the ripple current amplitude increases Table 1 List of CLP of components with stressors, common failure modes and effects on the micro inverter with the reduction of capacitance, a higher ripple current may result, causing greater Joule heating, and pushing the micro inverters towards capacitor dry out failure.

TABLE 1

LIST OF CLP OF COMPONENTS

| CLP Component | Common failure modes | Stressors | System-wide manifestation |
|---|---|---|---|
| MOSFET | die attach breakdown, wire bond fatigue, dopant drift | Thermal stress, RH, Power cycling, voltage | Reduced efficiency, short circuit module, excess heat |
| Diodes | die attach breakdown, wire bond fatigue, dopant drift | Thermal stress, RH, Power cycling, voltage | Reduced efficiency, short circuit module |
| Capacitors | electrolyte evaporation, dielectric breakdown | Thermal stress, RH, Current surge, high voltage | Reduced efficiency, increase ripple amplitude |
| Inductor | ferrite cracking | Thermal stress, high current | Reduced efficiency, excess heat |

where RH= Relative humidity

Even more, ripple current is highest at solar noon time when the solar irradiance at its peak, and this is when the micro inverter temperature is also highest. Therefore, a time series study of noon time data can provide important thermal information that can help one to understand the degradation mechanism of the micro inverter better. MOSFET failure can occur due to rapid heat buildup on the die package as observed in the case of IGBT during the power cycle [14-15]. Heat buildup in the die degrades the die attachments and causes thermal stress that possibly lead other failures such as wire bond breakage. Additionally, a sudden inrush of current through the inductor or a blocking voltage surge in the inductor can induce an avalanche failure of the MOSFET. The likelihood of avalanche failure is higher at solar noon time due to high power-voltage current conditions.

### 3.1 Power Loss inside Micro inverter

The power loss inside micro inverters falls into two categories: switching loss and inductor loss. Switching loss occur at the MOSFETs in the resonant inverter [16]. Switching losses occur because the only time that both the drain-source voltage and current are nonzero is during the ON-OFF transition times. This loss mechanism is reduced with high speed MOSFETs, with low recovery times, or by using a Zero Voltage Switch topology (ZVS). In ZVS, a resonant condition between the transformer leakage inductance and output capacitance of the MOSFET allow for the output capacitance to be fully discharged before the MOSFET switches ON. Conduction loss is related to the drain-source resistance ($R_{ds}$) and RMS current ($I_{switchRMS}$) through the MOSFET. The charging-discharging loss is related to the gate charge ($Q_g$), gate source voltage ($V_{gs}$) and switching frequency ($f_{switch}$) [17]. The expression for switching power loss ($P_{switchloss}$) is:

$$P_{switchloss} = I_{switchRMS}^2 R_{ds} + 2Q_g V_{gs} f_{switch} \quad ....(1)$$

Inductor loss is comprised of core and winding losses. Core loss can be estimated by Steinmetz equation$_2$ for core loss:

$$P_{coreloss} = V_c k f^{\alpha} B_{peak}^{\beta} \quad \text{....(2)}$$

Here $P_{coreloss}$ is the loss in the core, $V_c$ is the core volume, f is the inductor current frequency, $B_{peak}^{\beta}$ is the amplitude of core flux density and α, β, k are the Steinmetz parameters. Winding loss is associated with RMS current ($I_{RMS}^2$) through the inductor and AC resistance ($R_{L.AC}$ ) of the inductor. It can be expressed as:

$$P_{windingloss} = I_{RMS}^2 R_{L.AC} \quad \text{....(3)}$$

The inductor power loss is larger than switching loss due to the large volume and AC resistance of inductor. The inductor power loss does not have a significant effect on the inductor. However, it forces the neighboring components to operate to high temperature environment. The switching loss induce periodic thermal stress on the MOSFETs and can lead to die degradation.

### 3.2 Reliability of Micro inverters

The reliability of all components of the entire PV system must be considered to minimize failure and maintenance and enhance safety. In another study conducted between 2003-2007, the number of string inverter failures was at least 4 times higher Figure 3 than the failure of any other component. As discussed before, various CLP components of micro inverters (described in Table 1) are sensitive to thermal stress. However, the micro inverters must withstand high thermal stress conditions, particularly at the solar noon time when power and ambient temperature are typically highest. Additional stress may occur when the power output of the PV module saturates the microinverters. Morning and afternoon lowlight conditions can put the microinverter into a high frequency turn on and off state, which can be a potential source of thermal stress and current surge. Since microinverters have to be installed outdoors, these systems must also endure a wide variety of climate conditions, including hot-dry, hot-humid and, freezing, for example. These conditions can induce various degradation mechanism. However, the reliability of microinverters has not studied intensively. As discussed above, microinverters are similar to string inverter technology although one major difference is the amount of power that each must handle and the boost ratio from DC-AC voltages. None the less, they are both expected to suffer similar kinds of reliability issue under a real-world working environment. First generation microinverters exhibited very poor reliability in real-world operation [19] that was one of the reasons behind their demise.

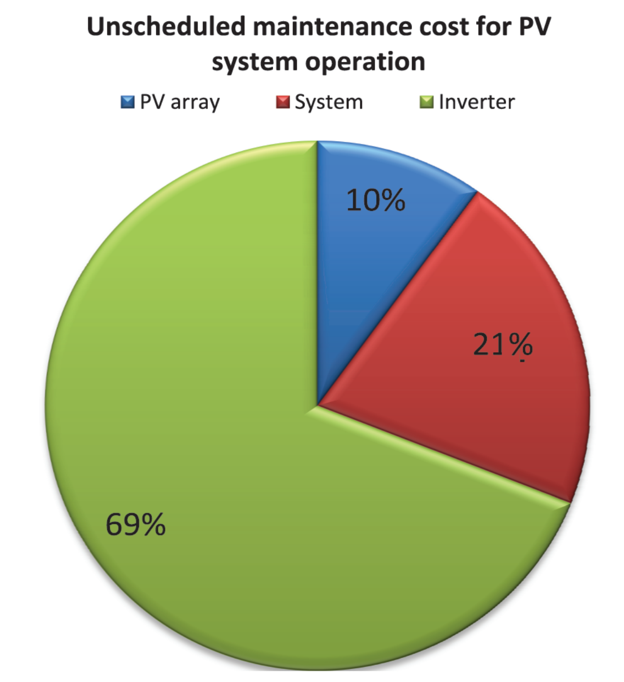


FIG. 3 MAINTENANCE COST FOR PV

Failure count for components of a PV system Researchers across the world have worked on studying and improving the reliability of the string inverter system. For example, Rohouma *et al.* [19] (2007) studied and compared the reliability of central, string and module integrated inverters (microinverters) where they found the average useful life of the microinverters is long compare to the string and central inverters. Additionally, they found that cable losses, and shading and mismatch losses is lower in microinverters compared to the other configurations.

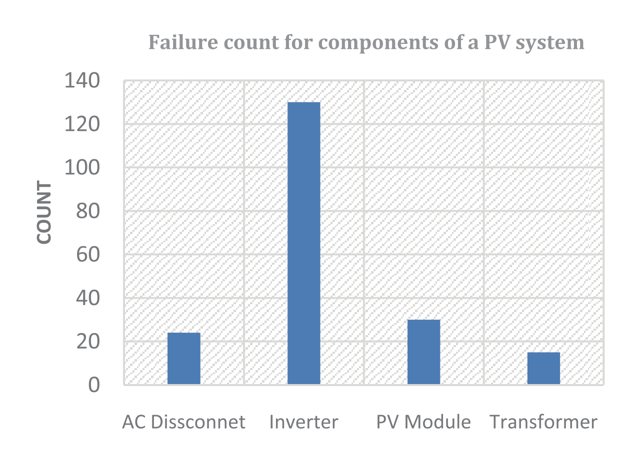


FIG 4. FAILURE COUNT FOR COMPONENT OF A PV SYSTEM

In their study, the failure rates of PV system components were assumed to be constant. Ristow *et al.* [20] (2008) proposed a prediction model for string inverters using the subsystem reliability. For their study, the string inverters were divided into following subsystems: storage-capacitor subsystem, power-stage-drive subsystem, cooling subsystem and isolation transformer.

FIG. 5 ROOF TOP MICRO INVERTER

They found capacitor failures dominate over other types of subsystem failures. According to the model, the most failure-prone devices are power MOSFETs and their failure is related to power dissipation. However, the failure rates can be very different in different environmental and operating conditions since the stress development rate and the total stress vary with environmental and operating conditions. To understand why consistent failure rates might not be an appropriate assumption, consider two scenarios in which one is mounted on a roof and another is located on a dual-axis tracker (on the ground). In a roof setup, the microinverter may not be exposed to sufficient wind to provide cooling. This is because the distance between PV modules and microinverters in a roof setup shown in Figure 5 is very small. As a result, the roof surface absorbs radiated heat, becomes hot and can lead to subsequent heating and thermal stress in the microinverter. For the scenario of the dual-axis tracker shown in Figure 6, the backside of the PV module and microinverter is open. There is a larger exposure to wind and no hot roof present to cause additional heating. Therefore, the thermal conditions and stresses experienced by the microinverters in both cases will be very different.

FIG. 6 DUAL AXIS TRACKING

## 4.0 MICRO INVERTER DESIGN

Mechanical packaging is critical for wicking away heat, protecting parts from dirt and humidity, and making installation uncomplicated. This experience is critical in comprehending real-world operating conditions, a microinverter must work outdoors with limited airflow in the heat of a rooftop, in a hot climate, and survive rain, ice, snow, thunderstorms and the salty air near an ocean. This operation must be reliable for many years, especially since these rooftop microinverters are beneath PV panels and not readily accessible for maintenance. The inverters must be robust enough to handle any vibration or drops encountered during shipping and installation.

This reduces internally-generated heat which must otherwise be removed, reduces the total number of components required and enables all the components inside the micro inverter to go on a single printed circuit board. The reduced component count results in lower defects and higher reliability. Internally-generated electronic noise is a common byproduct of inverter circuits. The traditional way to handle this is for a circuit design to add more components and circuit board space to filter out the noise.

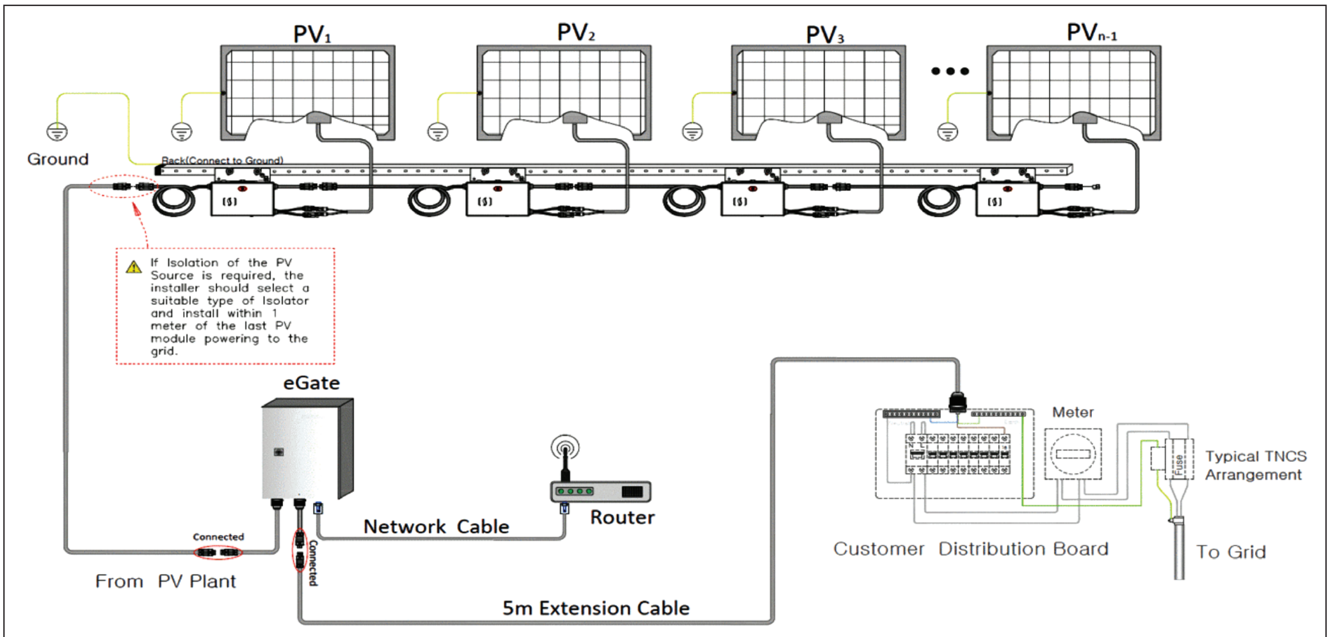


FIG. 7 GRID CONNECTED MICRO INVERTER SETUP

Micro inverter circuitry employs advanced techniques to drastically reduce those internal noise-generating voltage spikes. This circuit design reduces stress on internal components and results in longer inverter life shown in Figure 7.

### 4.1 Electronic component selection

Most electronic equipment has aluminum electrolytic capacitors inside; these are widely used in power electronics, are economical, and are familiar and widely available, but they are quite susceptible to performance degradation from heat. Avoiding them significantly increases long-term reliability in high temperature environments. Micro inverters only utilize thin film capacitors, which are far better suited for high reliability applications. Other electronic components were carefully selected to avoid operation close to their rated voltage, current and temperature limits, even during midday startup and shutdown, or during voltage surges, dips, or sudden changes in current due to shading, grid failures or dropouts.

### 4.2 Thermal considerations and packaging

Considerations for the design of the micro inverter chassis and packaging included ease of installation, ability to wick out heat, resistance to corrosion, temperature swings and shipping vibration, safety, and avoiding the need for fans. If a piece of electronic equipment has fans, then its reliability is quite dependent on those fans, and they're best monitored continuously and replaced before they fail. Micro inverters are designed without fans or other moving parts to avoid the need for such maintenance

## 5.0 INFLUENCE OF IRRADIANCE ON PV MODULE AND MICROINVERTER TEMPERATURE

Irradiance is the source of energy for the PV modules, and therefore the PV modules back sheet temperature is strongly correlated with irradiance. This is because the amount of radiated energy received by the microinverter from the PV modules' back sheet is therefore also small. In fact, the difference between ambient temperature and PV module back sheet temperature is about 0.88°C to 1.12°C.

### 5.1 Influence of AC power output and PV module temperature on micro inverter temperature

The PV module plays an important role in influencing the microinverter temperature, and here we consider both the direct effect of power output and module temperature. the power output of the microinverters correlates well to the power output of the PV modules. This inverse relationship occurs because at higher operating temperatures, the open circuit voltage and fill factor decrease significantly with a slight increase in short circuit current [22]. As a result, the maximum power output from the PV module typically decreases with an increase in PV module temperature. This relationship is also evident when a PV module is not generating power at sufficient irradiance such that all the irradiance received by the PV module converts to heat. Therefore, the temperature of the PV module becomes higher than the power generating conditions of the PV module. Since the PV module back sheet temperature is a heat source for the microinverter, similar high temperature trends are also observed during microinverter back sheet temperature at non power generating periods.

### 5.2 Influence of ambient conditions on microinverter temperature

As discussed above, the microinverters do not receive direct irradiance from the sun. They do, nonetheless, transfer heat with the surroundings (ambient conditions) and with the PV modules themselves. This can be seen from the fact that the correlation between microinverter temperature and irradiance is lower than the correlation between PV module back sheet temperature and irradiance. In the morning at low irradiance (irradiance below 60 $W/m^2$), the microinverter temperature is almost equal to the ambient temperature. The radiant energy received from the PV module back sheet and energy loss during DC to AC conversion are the main two contributors to the additional temperature rise of the microinverter at noon time. These three parameters are therefore critical factors for the predictive model as discussed in more detail below. Wind speed is the variable that determines the magnitude of the convection heat transfer rate to/from the PV module and microinverter back sheet.

## 6.0 CONCLUSIONS

The main conclusions follow,

i. The PV module back sheet temperature is generally higher for lower power producing PV module brands.

ii. Additionally, the PV module temperature generally determines the temperature rise of the microinverter at noon time.

iii. However, if the temperature of PV modules is similar, AC power output effects on the microinverter temperature become important. Even. One may expect thermal behavior to be different on a roof mounted system than on a dual-axis tracker, since the gap between roof surface and PV module back sheet is about 10 inches and microinverters are installed halfway in the gap.

iv. In the dual-axis system, the backside to PV module is open and therefore radiated heat will be lost into the open surroundings.

v. This would not be the case for the roof mounted systems, thereby trapping some of the heat within the small enclosure between roof and PV module.

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