Operating Temperatures of Open-Rack Installed Photovoltaic Inverters

Zhang, Z.^{1,2}, Wang, L.¹, Kurtz, S.², Wu, J.¹, Quan, P.³, Sorensen, R.⁴, Liu, S.¹, Bai, J. B.¹, Zhu, Z. W.¹,

1. The college of mechanical and electrical engineering, Hohai University, Changzhou, Jiangsu 213022, China;
2. National Renewable Energy Laboratory, Golden, Colorado, USA
3. State Key Lab of Photovoltaic Science and Technology, Trina Solar Co. Ltd., Changzhou, China
4. Sandia National Laboratories, Albuquerque, New Mexico, USA

Abstract -- This paper presents a model for evaluating the heat-sink and component temperatures of open-rack installed photovoltaic inverters. These temperatures can be used for predicting inverter reliability. Inverter heat-sink temperatures were measured for inverters connected to three grid-connected PV (photovoltaic) test systems in Golden, Colorado, US. A model is proposed for calculating the inverter heat-sink temperature based on the ambient temperature, the ratio of the consumed power to the rated power of the inverter, and the measured wind speed. To verify and study this model, more than one year of inverter DC /AC power, irradiance, wind speed, and heat sink temperature rise data were collected and analyzed. The model is shown to be accurate in predicting average inverter temperatures, but will require further refinement for prediction of transient temperatures.

Index Terms – Inverter, photovoltaic system, operating temperature, reliability.

1. Introduction

PV Inverters are an integral part of a PV system and must function properly for the system output to be optimized. The lifecycle reliability of power electronic devices is highly dependent on operating temperature, which depends on loads and ambient conditions^[1]. In air-cooled inverters fans and heat sinks are employed to mitigate heating of components in an attempt to improve long-term reliability^[2]. Operating temperature is often correlated with the mean time between failure (MTBF) of electrical components^[3-8]. Xavier Perpina analyzed the impact of a nonuniform temperature distribution inside insulated-gate bipolar transistor (IGBT) power modules on the reliability of railway power inverters^[8]. The interaction between the chosen cooling system and the power module was considered in detail. He mentioned that it must also be ensured that the temperature swings in IGBT modules do not exceed a certain critical value. Cuauhtemoc Rodriguez's study showed that the reliability of AC module depended on many factors, one of which was ambient temperature^[3]. Freddy Chan presented the reliability-based analysis of three hard-switching inverters^[4]. A comparison between the topologies was performed, and both the components and the stress factor with the highest contribution to the failure rate were identified. His paper showed that the operating temperature was a matter of

concern from the device selection perspective. An approach to PV inverter-reliability analysis was proposed based on inverter subsystems and operating environment in Alan Ristow's paper. It used estimates of inverter-component reliability in combination with Monte Carlo simulation to assess the expected availability of a particular inverter design. To increase the high temperature reliability of PV inverters, Mahshid Amirabadi proposed converter a single stage power conversion system with zero voltage turn on and soft turn off of the switches. This converter was formed by a parallel ac inductor/capacitor (LC) pair having low reactive ratings. It didn't contain any electrolytic capacitor which increases the reliability of this converter to a great extent. Three of these inverters were installed at three different commercial facilities in Texas, USA, to evaluate the long-term performance of the proposed inverter.^[9]

It is important to have an accurate value of the components temperature in the actual application. Reference^[6] presented simplified models for PV inverter temperature evaluation, which described the temperature rise of the inverter housing as a linear function of incident irradiance. The inverter component temperature formula was introduced in reference^[10], where IGBT and diode junction temperatures within the inverter were calculated using the operating powers of these components. Some publications introduced inverter component power loss and finite element thermal modeling of inverter heat sink(IHS) analysis^[11]. There are also many publications focusing on temperature assessment of PV modules and solar heat collectors^[12-14]. Whereas, fewer ones discuss the temperature calculation and reliability evaluation of inverters, from a point of view of the environmental and operating conditions for PV systems, such as irradiance, ambient temperature and PV system configuration. Knowledge of the thermal history of individual components, such as capacitors, IGBTs, transformers and circuit boards may be useful in assessing system reliability. The general temperature calculations for inverter components can be used in an assessment of inverter and/or component reliability. Assumed a thermally activated degradation mechanism, a cumulative exposure model with the temperature data taken from the inverters can be used to evaluate the failure-time distribution^[20]. Some inverters were designed to use temperature-dependent derating to protect sensitive semiconductor components from overheating. When the

monitored components reach the maximum allowable temperature, the device shifts its operating point to a lower power^[1, 24].

This paper proposes a temperature calculation and reliability evaluation method for open-rack installed PV inverters. Inverters may operate at a wide range of temperatures. A comprehensive model for predicting inverter temperatures as a function of environmental and operational conditions for all types of inverters is beyond the scope of this paper, but we take an initial step in that direction by developing a model to predict the IHS temperature in an open-rack installation. This model must be extended to be able to predict component temperature data; for the reliability calculations we use temperatures measured directly for the components of interest. To verify a model of inverter temperature rise and calculate wind speed factor and heat sink factor of the inverter, three PV inverters were analyzed. The component operating temperature results are demonstrated and discussed.

2. Heat balance for inverters

Some publications introduced a component temperature calculation model for power transformers^[15]. According to the IEC 60076-7, loading guide for oil immersed power transformers, the hot spot temperature in a transformer winding is the sum of three components: the ambient temperature, the top oil temperature rise, and the hot spot temperature rise over the top oil temperature^[16]. Finally, the hot spot temperature of a component is calculated by adding the ambient temperature to the top oil temperature rise and to the hot spot temperature rise^[17]. The approach originating from power transformers is applicable to PV inverters. Similarly the PV inverter component temperature can be calculated by:

$$T_C = T_A + \Delta T_H + \Delta T_C \quad (1)$$

where T_A is ambient temperature, ΔT_H is heat sink temperature rise, ΔT_C is component temperature rise.

The inverter heat generated by the switching of power electronics is mostly diffused through aluminum heat sinks. The heat balance of a IHS is given by:

$$Q_A = Q_C + Q_R \quad (2)$$

where Q_C and Q_R are the heat exchanged by convection and by radiation from the IHS surface, respectively, and Q_A is the absorbed heat from the heat sink, which is dependent on the inverter-consumed power. These can be calculated by:

$$Q_A = P_{dc} - P_{ac} \quad (3)$$

$$Q_C = H_w \times A(T_H - T_A) = H_w \times A \times \Delta T_H \quad (4)$$

$$Q_R = A \times \sigma(T_H^4 - T_E^4) \quad (5)$$

where P_{dc} , P_{ac} , H_w , A , σ , T_H , T_A and T_E respectively represent the inverter input DC power, output AC power, convection heat transfer coefficient, surface area of heat sink, Stefan Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$), IHS temperature, ambient temperature (air temperature around heat sink), environment temperature (inverter shelf or cover temperature).

Generally, Q_C is much larger than Q_R . To simplify the equation, we neglect Q_R , and the heat balance of the inverter can be approximately expressed as follows:

$$\begin{aligned} Q_A &= Q_C = H_w \times A(T_H - T_A) \\ &= A \times H_w \times \Delta T = P_{dc} - P_{ac} \end{aligned} \quad (6)$$

where ΔT_H is the temperature difference between the IHS and ambient air (the air around the inverter):

$$\Delta T_H = \frac{(P_{dc} - P_{ac})}{A \times H_w} \quad (7)$$

The convection heat transfer coefficient H_w is dependent on wind speed. There are many previous publications focused on the correlation between convective heat transfer and wind speed. One of the earliest experimental studies of wind induced forced convective heat transfer was described by McAdams in 1954^[18], who performed experiments on a heated 0.5 m^2 copper plate mounted vertically in a wind tunnel. Based on experimental data of Jurges, McAdams reported a correlation between the wind-induced convective heat transfer coefficient and the wind speed as^[18, 19]

$$H_w = 5.7 + 3.8V_w, \quad V_w \leq 5 \text{ m/s} \quad (8)$$

where V_w is the wind speed.

Kumar et al. (2010) studied the heat transfer of a flat solar heat collector, and proposed two formulas of convection heat transfer coefficient as follows^[12]:

$$\begin{aligned} H_w &= (6.9 \pm 0.05) + (3.87 \pm 0.13)V_w, \\ V_w &\leq 1.12 \text{ m/s} \end{aligned} \quad (9)$$

Based on the above research result, the convective heat transfer coefficient for an open rack installed inverter may be given by:

$$H_w = a + b \times V_w, \quad V_w \leq 5 \text{ m/s} \quad (10)$$

Combining equations (6) and (10),

$$\Delta T_H = \frac{(P_{dc} - P_{ac})}{A \times (a + b \times V_w)} \quad (11a)$$

In this work, we propose to reference the inverter efficiency to the rated power of the inverter, in order to help the coefficients be more consistent from inverter to inverter. We also propose to replace the area, A , and the two coefficients, a and b , with two new coefficients k and c because: 1) the area, A , of the heat sink is difficult to define or measure, and 2) replacing a and b with c and k makes the coefficients more independent of each other, giving:

$$\Delta T_H = \frac{k}{(1 + c \times V_w)} \times \frac{(P_{dc} - P_{ac})}{P_R} \quad (11b)$$

where, P_R c and k represent the rated power of the inverter, wind speed factor and heat sink factor ($V_w = 0$) of the inverter, respectively.

Formula 11b also can be expressed as:

$$\Delta T_H = K_{ws} \times \frac{P_{cpr}}{k} \quad (11c)$$

$$K_{ws} = \frac{k}{(1 + c \times V_w)} \quad (12)$$

$$P_{cpr} = \frac{(P_{dc} - P_{ac})}{P_R} \quad (13)$$

where K_{ws} is defined as the heat dissipation coefficient that is a function of wind speed, and P_{cpr} is the consumed power ratio (CPR) of the inverter.

The temperature rise shows substantial variability with wind speed; it can be useful to adjust the data so that the temperature rise can be evaluated without considering the effects of wind. Based on Eq. (12) and (11c), we adjust the IHS temperature rise measured at, V_w , $\Delta T_{H_{V_w}}$, to the corresponding temperature rise at the zero wind speed condition ($V_w = 0$), ΔT_{H_0} :

$$\Delta T_{H_0} = (1 + c \times V_w) \times \Delta T_{H_{V_w}} \quad (14)$$

3. Experiment

3.1 Test system introduction

Three grid-connected PV systems were studied in Golden, Colorado, US, as shown in Fig.1. Three inverters, S1, S2 and S3, were installed to the north of each PV array, underneath the open rack, about 0.4-0.5m above ground. Each PV module is about 210Wp with dimensions of 0.8m×1.6m. The bottoms of lower PV modules are about 1.2m distant from ground. Temperature sensors were fixed in each IHS. The wind speed sensor was installed to the northeast of PV inverters for measuring wind speed at about 1m above the top of PV array. The peak power of each PV system is 1.5-2kWp.

During the period of more than one year (from Jan., 2011 to Apr., 2012), the inverter DC and AC power, irradiance, wind speed and INS temperature rise were recorded. Equation 11b was used to fit the measured data. To verify this model, heat sink temperature rise data (1 min averaged per data point) were collected. To decrease the snow and sunshine impact, the data were sorted by the time and ratio between DC power and irradiance; data related to times when direct sunshine or snow could be found on the inverter surface were deleted in the plotting. And abnormal data, such as negative values for DC power and AC power data were removed.

The fitting results indicate that the k and c are 454 (°C) and 0.29 (s/m), respectively, for inverter S3. Similar analysis on other inverters found k is in the range of 450 - 600 (°C) and c is from 0.20 to 0.30 (s/m), as shown in Table 1. Comparing with inverter S3, S1 and S2 have higher heat sink factors (k), which implies poorer heat diffusion performance of the inverter.

3.2 Wind speed factor

Inverter heat dissipation is dependent on the local wind speed. Fig.2 shows the measured temperature rise of inverter S3, correlated with inverter CPR at different wind speeds. The temperature rise is plotted based on one year (from Jan., 2011 to Jan., 2012) of data sorted by wind speed. The heat dissipation factor for different wind speeds, K_{ws} , can be deduced by calculating the slop of the linearity fitted from the scatter data, as diagramed in Fig. 2.. According to the wind-speed factors shown in Table 1, modeled heat dissipation factors for different wind speeds can be derived using Eq. 12. Comparison between the modeled and measured heat dissipation factors of inverter S3 is shown in Fig. 3(a). The modeled heat dissipation factor deviates from the measured value by < 10%. Similarly, we compare the modeled and measured heat dissipation factors of inverter S1 and S2, as shown in Fig.3 (b). The difference between modeled and tested heat dissipation factor is also < 10% for these two inverters. Therefore, the proposed wind speed factor, c , and Eq. 11b can be used to approximately evaluate the wind speed effect on heat diffusion for open-rack installed PV inverters. The measured temperature rise deviation from the fitting linearity in Fig.2 will be discussed in section 3.5.

3.3 Heat-sink factor

Using the wind speed factors discussed above, all of the temperature rise data of IHSs can be modified and unified to the same wind speed (0 m/s) condition using formula 14. The wind-speed corrected data are plotted in Figs. 4 to show the correlation between IHS temperature rise and CPR for 3 inverters independent of the wind speed condition. The average temperature rise shown in the figures were obtained by averaging 50 different temperature values at the same CPR and corrected for wind speed. The heat-sink factor varies with the type of inverter. The model error for a temperature deviation range of $\pm 10^\circ\text{C}$ for calculating one temperature point is obvious, but it is much more accurate for predicting the average value of inverter temperature. As shown in Figs. 4, the average inverter temperature rise is very close to modeled results based on the formulas in Table 1. Fig. 4(a) shows how instantaneous measurements of the inverter S3 temperature rise are correlated with the model ($R^2 = 0.71$). The fit is much better when the data are averaged ($R^2 = 0.97$). We obtained similar results for inverters S1 and S2, as shown in Fig. 4(b) and Fig. 4(c). These two figures imply there's still a temperature rise at zero consumed power, which is probably caused by the thermal lag combined with parasitic power due to the thermal capacity of the inverters. Some inverters have a parasitic power that may affect the temperature of individual components even when the inverters are enclosed, which was reported by our previous work^[20]. For the purpose of evaluating reliability of inverters, knowledge of the average temperature may be adequate, alleviating the need to develop a transient model, though degradation processes that have high activation energies may be dominated by the short times spent at high temperatures. The omission of treatment of data compromised by snow is unlikely to affect reliability, but when inverters are deployed in direct sun, the higher temperatures may decrease the reliability. Some manufacturers require inverters mounting in a consistently shaded location. For inverters mounted in full sun, the model must be further modified before reliability assessments can be completed since the sun exposure could shorten the service life of the inverter.

3.4 Result and discussion for CPR and AC power effect

Previously published work treats inverter efficiency as constant and uses AC power instead of CPR for calculation of the inverter temperature rise^[6, 10]. To show the difference of effect between AC power and CPR for IHS temperature rise, 3 groups (3 inverters) of temperature rise curves were selected for 3 typical sunny days for PV inverters S1, S2, and S3. The three days were taken from winter, spring and summer. The data were filtered to remove times when there was snow or direct sunshine on the IHS surface. (These situations need to be modeled differently.) Fig.7 (a) shows the correlation between AC power and IHS temperature rise with correction for the wind speed according to Eq. 11b. Fig.5 (b) shows the correlation between CPR and IHS temperature rise with correction for wind speed. The inverter temperature rise data shown in Fig.7 (a) and Fig.7 (b) are corrected for the modeled effect of wind speed based on equation 14. Treating the inverter efficiency or power loss percentage as constant and using AC power instead of inverter CPR, the fit of inverter temperature rise shown in Fig. 5(a) shows a y-axis intercept

well above the origin, reflecting parasitic power usage even when the inverter is not active. In contrast, the graph shown in Fig. 5(b) shows an intersection much closer to the origin, providing a simple model for how much the consumed power is causing the inverter temperature to increase. The field data of inverters can match equation (11b) with a correlation coefficient of 0.8 or more. In summary, inverter efficiency is varying with input DC power. It is important to introduce the CPR to calculate the IHS temperature.

3.5 Test results and model error analysis

The model of inverter temperature rise is based on the thermal steady state condition, while the actual field condition is dynamic. Variations in irradiance, wind speed and inverter installation introduce inaccuracies to the model.

We find, in Fig.4, that average measured temperature rise is a little higher than modeled in the condition of low inverter CPR, and a little lower at high inverter CPR. It may be caused by sun irradiance variations combined with parasitic power. When the sun irradiance decreases abruptly, inverter CPR will decline with inverter DC (direct current) power decrease (CPR depends on inverter efficiency and DC power). The modeled inverter temperature rise based on equation (11c) decreases immediately, while the actual inverter temperature decreases slowly. The measured inverter temperature will be higher than the modeled temperature due to the time lag resulting from the heat content of the inverter. We compare the measured and modeled temperature rise for different days (the figures are not shown in this paper), and find the inverter temperature model fits better for the sunny day. For the sunny day, the irradiance on the solar array surface is comparatively stable, which results in minimal variations of DC power and inverter CPR over a short time interval. For the partly cloudy day, the inverter DC power and CPR vary sharply with irradiance which results in a modeled temperature rise that lags the measured temperature. The inaccuracy of the inverter temperature model is more evident on the partly cloudy day because the model does not describe transient behavior.

The measured temperature rise deviation from the fitting trend line can be found in Fig.2 in section 3.2. To compare the measured and modeled temperature as a function of the wind speed, Fig. 6 was plotted to show modeled and measured inverter S3 temperature rise under high and low wind speed conditions. Compared to wind speeds of 0~0.1m/s, the correlation of the fit between inverter temperature and CPR is much better for the wind speed conditions of 8 m/s. For high wind speeds, the rapid rate of heat diffusion allows the inverter to quickly reach steady state. The model calculation of inverter temperature is based on the thermal steady state condition, so the measured temperature data shows better agreement with predictions for higher wind speeds. Though there is still some inaccuracy using this model to predict the transient temperature rise, the measured temperature data follow more closely the modeled line if the inverter heat transfer is relatively stable.

Sunshine on the IHS surface adds an additional heat source to those shown in equation 3, causing a deviation from the model. The data presented here were filtered to remove data associated with direct sunshine and/or snow coverage. The measured temperature will be different if there is some

sunshine on the surface of the IHS surface. Fig. 7 (a) shows measured and modeled temperature rise of a black IHS under shaded and unshaded conditions. Fig. 7 (b) shows similar data for a light colored inverter. The lower correlation factor (R) and higher value of heat sink factor (k) can be found for the same inverter in the unshaded condition with sunshine on the inverter surface. Direct sunshine on the inverter surface will lead to higher and less predictable inverter operating temperature. For black inverters, the temperature rise associated with direct sun was found to be up to 5°C; for inverters with a light color, the temperature rise under direct sunlight was < 3°C. As shown in Fig7 (a), (b), the temperature rise for an inverter with black colour has many data points close to zero, whereas the data points for light colour inverter start at higher temperatures. It may be caused by parasitic power usage even when the inverter is not active. The black inverter (S3) have better efficiency and lower power loss at low irradiance condition, while light colour inverter (S1, S2) have higher parasitic power to cause remarkable temperature rise even at night.

Overall it appears that the probability of modeled inverter temperature rise deviation is variable in different CPR or wind speed conditions. There are still some differences between modeled and observed inverter temperature rise. However, those temperature deviations caused by dynamic irradiance or wind speed can be mainly counteracted by averaging the measured value. For an open-rack installed inverter with no direct sunshine on its surface, the model is quite good at predicting the average inverter temperature.

4. Inverter component temperature analysis

The computational model of IHS temperature rise is introduced above. The electronic components are contained within the inverter. The heat transfer coefficients between the components and the heat sink are relatively stable. The temperature difference between the inverter components and the heat sink can be approximated by^[21]:

$$\Delta T_C = k' \times P_C \quad (15)$$

where P_C is the consumed power of each inverter component and k' is the heat transfer coefficient of the inverter component. The inverter component's temperature, T_C , can be calculated by:

$$T_C = T_H + \Delta T_C = T_H + k' \times P_C \quad (16)$$

where ΔT_C is the temperature difference between the inverter component and the heat sink. In general, each component may have a different level of heat dissipation and absorption, so equation 16 should be written for each component.

4.1 Capacitor temperature rise

The capacitor and IGBT are two important components in inverters. The temperature of the capacitor not of the heat sink is the most critical component limiting the lifetime of the PV inverter in special if it is an aluminium electrolytic capacitor. Capacitor failure can be a major factor contributing to inverter failure. Consumed power in a capacitor can be attributed to dielectric hysteresis and dielectric leakage^[22].

$$P_{cc} = I_r^2 \times R_s + I_L \times V_L \quad (17)$$

where I_r is RMS (Root Mean Square) ripple current found at the capacitor, R_s is the equivalent series resistance of the capacitor, I_L is the dielectric leakage current in the capacitor, and V_L is the ripple voltage of the capacitor. RMS ripple current I_r can be calculated by:

$$I_r = \frac{P_o}{\sqrt{2} \times V_d} \quad (18)$$

where P_o is the output power of the inverter, and V_d is the DC input voltage of the inverter. Therefore, the core temperature rise of a capacitor at steady state can be approximated as follows:

$$\Delta T_{cc} = K'_c \times P_{cc} = K'_c \times (I_r^2 \times R_s + I_L \times V_L)$$

Ordinarily the leakage current I_L is so small that for all practical purposes it is ignored.

$$\begin{aligned} \Delta T_{cc} &\approx K'_c \times R_s \times I_r^2 = \frac{1}{2} K'_c \times R_s \times \left(\frac{P_o}{V_d}\right)^2 \\ &= \frac{1}{2} K'_c \times R_s \times I_{inverter}^2 \end{aligned} \quad (19)$$

where K'_c is the heat transfer coefficient of the capacitor, $I_{inverter}$ is the inverter input current. ΔT_{cc} is proportional to $I_{inverter}^2$ when we assume the series resistance to prevail.

4.2 IGBT temperature rise

Like power losses in any semiconductor component, consumed power in the IGBT (P_{ci}) can be divided in three groups: conduction losses (P_{cond}), switching losses (P_{sw}) and blocking (leakage) losses (P_b). Normally blocking losses are small and can be neglected^[23]. Therefore,

$$P_{ci} = P_{cond} + P_{sw} + P_b \approx P_{cond} + P_{sw} \quad (20)$$

IGBT conduction losses can be calculated using an IGBT approximation with a series connection of DC voltage source (U_{ceo}) representing the IGBT on-state zero-current collector-emitter voltage and a collector-emitter on-state resistance (r_c): The average value of the IGBT conduction losses is:

$$P_{cond} = U_{ceo} \times I_{av} + r_c \times I_{rms}^2 \quad (21)$$

where I_{av} is the average IGBT current and I_{rms} is the RMS value of the IGBT current.

The switching losses in the IGBT and the diode are the result of switching energies:

$$P_{sw} = f_{sw} (E_{onm} + E_{offm}) I_s / I_{nom} \quad (22)$$

where f_{sw} is the switch frequency, I_s is the operating current of the IGBT, and I_{nom} is the rated current of the IGBT. Therefore, the consumed power of the IGBT can be given by:

$$P_{ci} = P_{cond} + P_{sw} = U_{ceo} \times I_{av} + r_c \times I_{rms}^2 + \frac{f_{sw} (E_{onm} + E_{offm}) I_s}{I_{nom}} \quad (23)$$

The temperature rise of the IGBT at steady state can be approximated as:

$$\begin{aligned} \Delta T_{ci} &= k_i' \times P_{ci} \\ &= k_i' \times (U_{ceo} \times I_{av} + r_c \times I_{rms}^2 + \frac{f_{sw} (E_{onm} + E_{offm}) I_s}{I_{nom}}) \\ &= I_{inverter} \times [k_i' \times U_{ceo} \times \frac{I_{av}}{I_{inverter}} + k_i' \times \frac{f_{sw} (E_{onm} + E_{offm})}{I_{nom}} \times \frac{I_s}{I_{inverter}} \\ &\quad + I_{inverter} \times k_i' \times r_c \times (\frac{I_{rms}}{I_{inverter}})^2] \end{aligned}$$

$$= I_{inverter} (K_1 + K_2 \times I_{inverter}) \quad (24)$$

where K_1 and K_2 are defined temperature coefficients of the IGBT.

K_1 and K_2 can be expressed as:

$$K_1 = k_i' \times U_{ceo} \times \frac{I_{av}}{I_{inverter}} + k_i' \times \frac{f_{sw} (E_{onm} + E_{offm})}{I_{nom}} \times \frac{I_s}{I_{inverter}} \quad (25)$$

$$K_2 = k_i' \times r_c \times (\frac{I_{rms}}{I_{inverter}})^2 \quad (26)$$

The components temperatures of two grid-connected PV inverters installed inside the room were studied in Chang Zhou, Jiangsu, China. The peak power of each PV system for the experiment is 1.5-2kWp. Temperature sensors were fixed in each IGBT and capacitor. Fig.8 shows the IR mapping graphs for the operating temperature distribution of the inverter components. Components temperature, ambient temperature, irradiance, inverter input and output data were monitored from 3 Apr. to 26 Apr., 2015. As shown in Fig.9, the correlation of the fit between inverter components (Capacitors and IGBT) temperature rise ΔT_c and irradiance is excellent, while the inverter input current is roughly linearly associated with irradiance of 100-1000W/m².

5. Conclusions

This paper demonstrated a method for modeling IHS temperature as a function of the operating conditions and inverter characteristics. Based on analysis of three sets of inverter temperature data, we proposed a thermal model for the heat sink with an uncertainty of $\pm 10^\circ\text{C}$. Accuracy in predicting average inverter heat-sink temperatures was typically $\pm 3^\circ\text{C}$. The difference between modeled and measured heat dissipation factors for different wind speeds was less than 10% for the tested inverters.

The heat sink factors (k) and wind speed factors (c) differed for different types of inverters or different installation environments. Similar to nominal operating cell temperature (NOCT) and the power temperature coefficient of a solar module, the IHS factor (k) is an important quantity, which can reflect the thermal performance of a PV inverter.

We extended the study of the inverter heat-sink temperatures by summarizing related formulae that can be used for approximately predicting inverter component temperature. We also introduced how temperature profiles from inverter components can be analyzed to provide insight into inverter reliability (for thermal degradation mechanisms) and limited operating condition. A detailed understanding of inverter component temperature will require more study, but the modeled and measured heat-sink data elucidated 1) how the inverter temperatures are dependent on the ambient conditions even when the inverters are enclosed, 2) how parasitic power can affect the temperature of individual components, and 3) how the effects of wind and ambient temperature can be modeled to understand the IHS temperature.

ACKNOWLEDGMENT

The authors thank Nick Bosco and Chris Decline of the National Renewable Energy Laboratory, Qian Jiaqiang and

Xia Dengfu of Trina Solar Ltd. for reviewing the paper and supporting the experiments. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory, the China Natural Science Foundation of Jiangsu Province (BK20151173), and the Fundamental Research Funds for the Central Universities(2014B19614).

6. References

- [1] Alahmad M, Chaaban M.A, Lau S.K, et al. An adaptive utility interactive photovoltaic system based on a flexible switch matrix to optimize performance in real-time [J]. *Solar Energy*, 2012, 86(3): 951-963.
- [2] Albuquerque F.L, Moraes A.J, Guimaraes G.C, et al. Photovoltaic solar system connected to the electric power grid operating as active power generator and reactive power compensator [J]. *Solar Energy*, 2010, 84(7): 1310-1317.
- [3] Rodriguez C, Amaratunga G.A.J. Long-lifetime power inverter for photovoltaic AC modules [J]. *IEEE Transactions on Industrial Electronics*, 2008, 55(7): 2593-2601.
- [4] Chan F, Calleja H. Reliability Estimation of Three Single-Phase Topologies in Grid-Connected PV Systems [J]. *IEEE Transactions on Industrial Electronics*, 2011, 58(7): 2683-2689.
- [5] Antonios J, Ginot N, Batard C, et al. A model reduction approach for constructing compact dynamic thermal models of IGBT-modules of inverters [J]. *Microelectronics Journal*, 2012, 43(6): 345-352.
- [6] Ristow A, Begovic M, Pregelj A, et al. Development of a methodology for improving photovoltaic inverter reliability [J]. *IEEE Transactions on Industrial Electronics*, 2008, 55(7): 2581-2592.
- [7] DelaParra I, Marcos J, García M, Marroyo L. Improvement of a control strategy for PV power ramp-rate limitation using the inverters [J]. *Reduction of the associated energy losses*, *Solar Energy*, 127 (2016) :262-268.
- [8] Perpina X, Serviere J.F, Urresti-Ibanez J, et al. Analysis of Clamped Inductive Turnoff Failure in Railway Traction IGBT Power Modules Under Overload Conditions [J]. *Industrial Electronics, IEEE Transactions on*, 2011, 58(7): 2706-2714.
- [9] Amirabadi M, Balakrishnan A, Toliyat H.A., et al. High-Frequency AC-Link PV Inverter [J]. *Industrial Electronics, IEEE Transactions on*, 2014, 61(1): 281-291.
- [10] Peng Z, Yang W, Weidong X, et al. Reliability evaluation of grid-connected photovoltaic power systems [J]. *IEEE Transactions on Sustainable Energy*, 2012, 3(3): 379-389.
- [11] Aarniovuori L, Laurila L.I.E, Niemela M, et al. Measurements and Simulations of DTC Voltage Source Converter and Induction Motor Losses [J]. *IEEE Transactions on Industrial Electronics*, 2012, 59(5): 2277-2287.
- [12] Kumar S, Mullick S.C. Wind heat transfer coefficient in solar collectors in outdoor conditions [J]. *Solar Energy*, 2010, 84(6): 956-963.
- [13] Aljoaba S.Z, Cramer A.M, Walcott B.L. Thermo-electrical modeling of light wavelength effects on photovoltaic cell performance [A]. 2011 37th IEEE Photovoltaic Specialists Conference (PVSC 2011) [C]. Seattle, WA, USA: 2011: 000192-000197.
- [14] Bharti R, Kuitche J, Tamizhmani M.G. Nominal operating cell temperature (NOCT): effects of module size, loading and solar spectrum [A]. Proceedings of the 2009 34th IEEE Photovoltaic Specialists Conference (PVSC 2009) [C]. Philadelphia, PA, USA: 2009: 6-12.
- [15] IEEE Guide for Loading Mineral-Oil-Immersed Power Transformers up to and Including 100 Mva With 55 Degrees C Or 65 Degrees C Average Winding Rise [S]1981.
- [16] Power transformers - Part 7: Loading guide for oil-immersed power transformers [S].
- [17] Daher S, Schmid J, Antunes F.L.M. Multilevel inverter topologies for stand-alone PV systems [J]. *IEEE Transactions on Industrial Electronics*, 2008, 55(7): 2703-2712.
- [18] McAdams. Heat Transmission [M]. New York: McGraw-Hill, 1954.
- [19] Aganza-Torres A, Cardenas V, Pacas M, et al. An efficiency comparative analysis of isolated multi-source grid-connected PV generation systems based on a HF-link micro-inverter approach [J]. *Solar Energy*, 127 (2016): 239-249.
- [20] Sorensen N.R, Thomas E.V, Quintana M.A, et al. Thermal Study of Inverter Components [R]. Golden, CO: NREL, 2012.
- [21] Alonso R, Roman E, Sanz A, et al. Analysis of Inverter-Voltage Influence on Distributed MPPT Architecture Performance [J]. *IEEE Transactions on Industrial Electronics*, 2012, 59(10): 3900-3907.
- [22] Sharma P, Bhatti T.S. A review on electrochemical double-layer capacitors [J]. *Energy Conversion and Management*, 2010, 51(12): 2901-2912.
- [23] Yuan B, Yang X, Zeng X, et al. Analysis and Design of a High Step-up Current-Fed Multiresonant DC-DC Converter With Low Circulating Energy and Zero-Current Switching for All Active Switches [J]. *IEEE Transactions on Industrial Electronics*, 2012, 59(2): 964-978.
- [24] Akbaba M. Matching three-phase AC loads to PVG for maximum power transfer using an enhanced version of the Akbaba model and double step-up converter [J]. *Solar Energy*, 2003, 75(1): 17-25.