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Operating temperatures of open-rack installed photovoltaic inverters

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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.

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 (Alahmad et al., 2012). In air-cooled inverters fans and heat sinks are employed to mitigate heating of components in an attempt to improve long-term reliability (Albuquerque et al., 2010). Operating temperature is often correlated with the mean time between failure (MTBF) of electrical components (Rodriguez and Amaratunga, 2008; Chan and Calleja, 2011; Antonios et al., 2012; Ristow et al., 2008; DelaParra et al., 2016; Perpina et al., 2011). 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 (Perpina et al., 2011). 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 (Rodriguez and Amaratunga, 2008). Freddy Chan presented the reliability-based analysis of three hard-switching inverters (Chan and Calleja, 2011). 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 (Amirabadi et al., 2014).

It is important to have an accurate value of the components temperature in the actual application. Ristow et al. (2008) 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 Peng et al. (2012), where IGBT and diode junction temperatures within the inverter were

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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 Aarniovuori et al., 2012. There are also many publications focusing on temperature assessment of PV modules and solar heat collectors (Kumar and Mullick, 2010; Aljoaba et al., 2011; Bharti et al., 2009). 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 (Sorensen et al., 2012). 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 (Alahmad et al., 2012; Akbaba, 2003).

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 (IEEE, 1981). 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 (Power transformers). 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 (Daher et al., 2008). The approach originating from power transformers is applicable to PV inverters. Similarly the PV inverter component temperature can be calculated by:

$$\mathrm{T_C} = \mathrm{T_A} + \Delta\mathrm{T_H} + \Delta\mathrm{T_C} \tag{1}$$

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:

$$Q_A = Q_C + Q_R \tag{2}$$

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:

$$Q_A = P_{dc} - P_{ac} \tag{3}$$

$$Q_C = \mathrm{Hw} \times \mathrm{A}(T_H - T_A) = H_w \times \mathrm{A} \times \Delta T_H \tag{4}$$

$$Q_R = \mathrm{A} \times \sigma\left(T_H^4 - T_E^4\right) \tag{5}$$

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 ($5.67 \times 10^{-8}\ \mathrm{W/m^2/K^4}$), 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:

$$Q_A = Q_C = H_w \times A(T_H - T_A) = A \times H_w \times \Delta T = P_{dc} - P_{ac} \tag{6}$$

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

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

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 (1954), 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 (McAdams, 1954; Aganza-Torres et al., 2016)

$$H_w = 5.7 + 3.8V_w, \quad V_w \leqslant 5\ \mathrm{m/s} \tag{8}$$

where V_w is the wind speed.

Kumar and Mullick (2010) studied the heat transfer of a flat solar heat collector, and proposed two formulas of convection heat transfer coefficient as follows:

$$H_w = (6.9 \pm 0.05) + (3.87 \pm 0.13)V_w, \quad V_w \leqslant 1.12\ \mathrm{m/s} \tag{9}$$

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

$$H_w = a + b \times V_w, \quad V_w \leqslant 5\ \mathrm{m/s} \tag{10}$$

Combining Eqs. (6) and (10),

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

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:

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

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:

$$\Delta T_H = K_{ws} \times P_{cpr} \tag{11c}$$