RELIABILITY CONSIDERATION OF LOW-POWER GRID-TIED INVERTER FOR PHOTOVOLTAIC APPLICATION

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ABSTRACT: In recent years PV modules have been improved evidently. An excellent reliability has been validated corresponding to Mean Time between Failure (MTBF) between 500 and 6000 years respectively in commercial utility power systems [1]. Manufactures can provide performance guarantees for PV modules at least for 20 years. If an average inverter lifetime of 5 years is assumed, it is evident that the overall reliability of PV systems [PVSs] with integrated inverter is determined chiefly by the inverter itself. It must be considered that the module integration of the inverter results in harsh environment especially like high temperature stress.
This paper presents a single stage integrated inverter applied in low power situation, analyzes the failure rate, contrasts three different approaches of reliability prediction for electronic equipment and simulates the thermal behavior of the integration PVSs. As a result, a high reliability PV inverter has been achieved successfully by employing film capacitors and semiconductor power modules instead of conventional electrolytic capacitor and discrete power switches. Moreover, an optimum housing design in terms of thermal management improves the inverter reliability.
Keywords: Reliability, AC-Modules, Inverter, Modelling, Module Integration

1 INTRODUCTION

In nowadays PV technology has been widely known as one special means to convert and transmit the solar energy via making use of the silicon cells integrated into one PV module. In Germany and Japan, approximately 2863 MW and 1708 MW of PV capacity were installed until the end of 2008 respectively. Meanwhile, the annual growing rate at installation capacity in the IEA PVPS countries was 36%, and Germany's accumulated installed capacity grew at 50% and Japan's growth rate was fairly steady at 20% in 2006 [2]. However, it has been verified that approximately 66% PV inverters have undergone troubles due to the most troublesome components [3]. Therefore, how to optimize and integrate the PV systems will be one crucial challenge to robust the system reliability.

As we known, the development and production of PVSs were addressed by high conversion efficiency, low failures and economic cost will be the principal challenge in the future [4]. Actually in current PV application market 75% PVSs is applied in grid-tied and micro-grid system. Accordingly, this paper will focus on grid-tied PVSs. Typical PV systems are composed of PV module and power converters or inverters, and both of the two blocks are tied as series connection. If any substantive block is defective, the whole PVSs is also announced to be out of operation. Due to rapid development of the thin-film techniques, PV module has been improved evidently which can warrant at least 20 years lifetime and also has validated excellent reliability corresponding to MTBF (Mean Time Between Failure) which could be ranged between 500 years and 6000 years [1]. If an average inverter lifetime of 5 years is assumed, the reliability of integrated PVSs is determined chiefly by the inverter configuration. Whereas how to configure and integrate the inverter with PV module and how to define and design will be one primary work package to improve and optimize PVSs reliability.

For grid-tied PVSs usually several separate modules are effectively linked as series strings configuration. Typically the connection between PV modules strings and PV inverter can be assorted as central inverters, multi-string inverters and module-integrated converter (MIC). Central inverters are often used in the large power PV installations, and strings of PV modules are connected in parallel. However, because of the module mismatch and uncertain shading especially in large power PV application, the energy yield might be reduced. Multi-string inverters are organized by one inverter with terminal for several independent PV module strings. Each module string is also equipped with an independent MPPT control function, and hereby it can correspondingly decrease energy losses caused due to system unbalance. In MIC PVSs each module is equipped with its own inverters shown in Fig 1. The recommended MIC is composed of 3-phase inverter and one PV module, and synchronously the MPPT control is embedded inside each inverter. MPPT block will be acted as to control each PV module for transferring solar energy effectually, and thus reduce the mismatch losses for the PVSs.

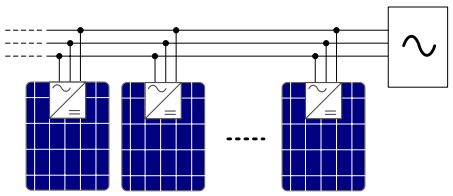


Figure 1: Module-integrated PV inverter

Be based upon mentioned PV system configurations, Proposed MIC concept can be provided with following unique features [5]:

- Minimal mismatch losses due to parallel connection of PV modules
- Independence Maximum Power Point Tracking
- No DC equipments
- Small losses at partial shading
- Potential cost reduction due to mass production
- Simple system configuration, easy installation

- High MTBF suggests a 20 years lifetime with 90% reliability

The significant reliability performance is a quite important requirement for the PVSs. Because MIC signifies that the inverter will be mounted tightly at back of PV module under outdoors conditions such as high temperature, variable humidity and so on. Therefore, integrated AC module should endure all those extraordinary burdens for implementing excellent reliability. In order to satisfy sufficiently so high reliability requirements because of basically 20 years lifetime from PV module, a high efficiency and reliable laboratory prototype of a compact low-power inverter has been implemented. Experiment results show maximum 96.5% efficiency through using reliable components. At the same time optimized thermal management provides the favorable operating environment for the sake of enhancing the inverter reliability. The purpose of thermal management is to remove redundant heat from decisive heat component without causing negatively effect on reliability of adjacent components, and sequentially to robust the system reliability.

At following this paper focuses on verifying the system reliability by using different reliability prediction models and critical components. Meanwhile, optimized housing is employed for improving the thermal management, and it will be verified by thermal simulation using FEM® simulation tool and practical field test at IWES.

2 SYSTEM DESIGN AND OPERATION

2.1 Inverter topology option

Conventional techniques about how to design MIC in principle focus on existing PV module with common low output voltage and the utilization of single-phase grid connection. Therefore, most of present inverters would be equipped with one additional stage achieving the boost function such as front-end boost converter and step-up transformer. In a result, above mentioned topology concept will increase the system complicacy, meanwhile lead to decrease the system reliability due to employing massive excess and unnecessary components. Moreover, a single-stage topology based on the Flyback converter has been demonstrated in [6]. Despite the fact that the Flyback converter can be operated with less part count, owing to lower transformer efficiency reflected on only maximal efficiency of 89%. Based on commercial application of PV inverter in the future, high efficiency and high reliability has been one essential standpoint for the development of MIC in next generation. Whereas, PV module producing low output voltage will increase the diameter of DC cable and high-capacity electrolytic capacitor used to supply system energy will be also very necessary. High-capacity electrolytic capacitor is one weakest point owing to lower lifetime [7]. Because MIC shall be operated at high temperature especially in summer, electrolytic capacitor will be sensitive to the variable temperature. As a result, for the sake of high reliability, film capacitor is recommended to be employed for improving the PVSs reliability obviously considering the thermal stress under critical climate conditions.

2.2 Selected approach and topology

In order to vanquish all drawbacks and limitations derivated above, a proposed approach has been given in figure 2. The chosen topology is known as Current Source Inverter (CSI). Due to three-phase grid connection the dc-link energy storage can be drastically reduced. No electrolytic capacitors are necessary which are generally very sensitive to temperature and issue in high failure rate. The implementation of a single-stage concept is facilitated by employing customized high-voltage PV modules (V_{mpp}=380V). Those modules are tailored for providing high voltage to eliminate the unnecessary dc-dc converter, thus could bring out the favorable operation condition through reducing total part count of MIC for further optimizing MIC reliability.

The common two-level voltage source inverter (VSI) might not be the best options for proposed application. When directly connected to the PV module, the VSI would require a high input voltage (V_{mpp}>700V) for proper sinusoidal current feed-in due to its buck type characteristic. Since the module voltage could exceed 1KV, in case of open circuit conditions and at low temperatures, the inverter electronic as well as system components are subject to enhanced requirements. For a reliable design the 1kV margin should be respected and the PV module voltage should be reduced accordingly. In this case the VSI must be equipped with an additional boost stage (BS)

Based on overall consideration, the proposed three-phase pulse width modulated (PWM) CSI is composed of a bridge with six reverse blocking switches (S1-S6). The dc link contains an inductor as the main energy storage component, one CL filter tied with the output which smoothens the pulsed phase currents from the dc link. A transient voltage suppressor diode D_Z provides a "freewheeling" path in the event of an unintended open circuit of the bridge. Even through the CSI exhibits higher conduction losses compared to VSI + BS, this option could be better balanced by lower switching stress and specifically smaller passive components [8]. On the other hand, the CSI is well suitable for MOSFETs since their intrinsic body diodes are inactive during commutation. These are generally considered to be poor in terms of switching losses. Moreover, the topology is capable of operating at moderated MPP voltage due to its inherent voltage-boost characteristic. However, to keep the voltage second balance across the dc inductor, there is an upper dc voltage limit, which is defined as the absolute minimum of the rectified phase-to-phase voltage [9].

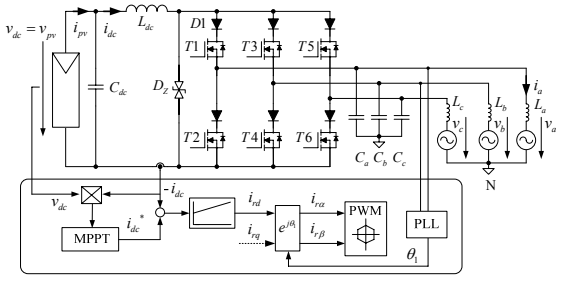


Figure 2: CSI Schematic with current-control block diagram for PV Module generation system

3 RELIABILITY PREDICTION APPROACHES

3.1 Lifetime consideration

Reliability (R (t)) is defined as the probability that a product performs its intended function without failure under specified environment conditions for a given period of time. And normally starting with the classic exponential expressions relationship supposes the model of random failures of a component without regarding as time moving. It also could be expressed to be one function of time, t (lifetime or operating time of the product), and the MTBF (MTBF=1/λ, λ defined as the system failure rate).

$$R(t) = e^{-\frac{t}{MTBF}} = e^{-t\lambda} \quad (1)$$

A lifetime prediction defines the time until one single unit is worn-out. The relationship between reliability and MTBF is depicted in figure 3 shown based on the different lifetime definition.

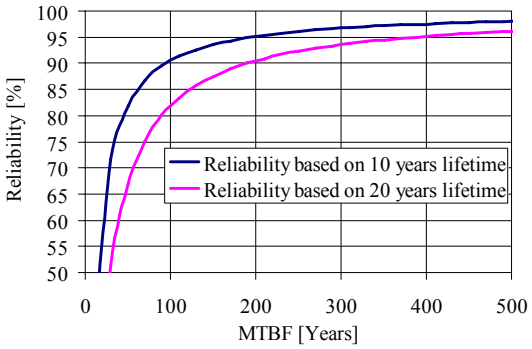


Figure 3: Reliability of the general definition

Table I: Typical components failure rate based on MIL-HB-217F [13]

Description	Type	FIT in 10^9 hrs	MTBF in years
Resistor	Carbon	10	11415
	Wire-wound	25	4566
	Film	50	2283
Capacitor	Electrolytic	1500	76
	Tantalum	1000	114
	Paper	500	228
	Ceramic	250	456
	Plastic Film	20	5707
Diodes	Silicon	50	2283
Transistors	Discrete Silicon	80	1426
IGBT Module	Silicon	1450	78
Power Module	Silicon Carbide	100	1141
Power Inductor	Copper Winding	50	2283
Transformer	Copper Winding	200	570
Connections	Soldered	10	11415
Conector	Per Pin	50	2283

The term reliability-prediction has been historically applied for estimating the field-reliability of a system from the 1950s to present [10]. Two primary category of reliability prediction can be classified by two groups denominated to empirical-based models and physics of failure [11]. Empirical-based model is only one estimation method to provide one relative accurate models to compute the failure rate of the electronics system, and the detail comparison of the different prediction approaches have been illustrated in [10][11][12]. Physicals-of-failure is established on the intrinsic failure factor which failures mechanisms are dominated by fundamental mechanical such as electrical stress, thermal stress and chemical composition. The specific contrasts have been enumerated in [12]. How to select the prediction models is according to the application environment and manufacture requirements in consideration. The failure rate of some typical components has been shown as Table **I** shown.

3.2 Capacitor lifetime

Table **I** shows that the electrolytic capacitor will produce great negative effect to the system reliability, whereas the plastic film capacitor has high MTBF for improving and optimizing the system reliability. In order to perform reliability prediction, the temperature is one rigorous condition to impact on the transmutation trend of the capacitor lifetime. The capacitor reliability can be calculated through below illustrated model [21]:

$$L_{OL} = L_{SL} \bullet \alpha_V \bullet 2^{\left(\frac{T_{ref} - T_{op}}{10}\right)} \quad (2)$$

L_{OL}: Operating life at operating temperature and voltage; L_{SL}: Reference service life; α_V: Applied voltage ratio which could be defined according to the different manufactures; T_{ref}: Reference temperature (40°C); T_{op} Operating temperature;

The following figure 4 shows the calculated lifetime of the different dielectric material capacitor. The calculation result showed that the polymer film capacitors have the higher lifetime compared with electrolytic capacitors under high temperature condition. Therefore, it should be suitable for the MIC application due to high temperature stress at normal operation.

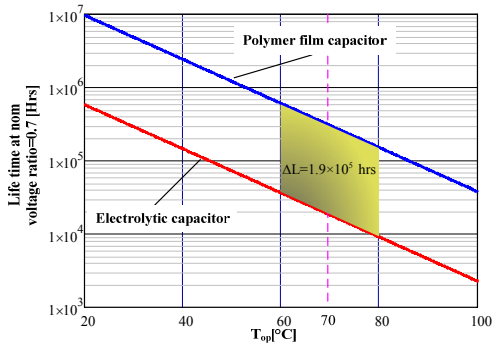


Figure 4: Lifetime for different dielectric capacitor

Constantly, Equivalent Series Resistance (ESR) also indicates a very important indication for electrolytic capacitor prediction. ESR could be expressed as below equation and would be increased 3 times with the volume of the electrolyte reduced by 40% due to long time operation [14].

$$\frac{ESR}{ESR_0} = \left(\frac{V_0}{V}\right)^2 \quad (3)$$

Where ESR_0 is initial ESR, V_0 is initial volume of electrolyte. According to the formula definition, the electrolytic capacitor failure prediction will be more weakness to be reputed to a failure [15].

Table II: ESR comparison of different dielectric

Dielectric	D.F (dissipation factor)	ESR (1uF cap) ohms
Aluminum Electro (50V)	10% at 120 Hz	132.629
Polyester	1% at 120 Hz	1.592
Polypropylene	0.1% at 1KHz	0.1592

Obviously, ESR of the film capacitor is much smaller than the same defined parameter like electrolytic capacitor as in table II shown:

Usually the internal maximum temperature T_{Cmax} of the capacitor can be roughly computed with [21]:

$$T_{Cmax} = T_a + I_{rm-dc}^2 \cdot R_{ESR}\left(T_C, f, DF\right) \cdot R_{th} \quad (4)$$

Where T_a is the ambient temperature, R_{ESR} is actual ESR, integrating the temperature T_c, f are frequency fit factor and DF is dissipation factor, R_{th} is the equivalent thermal resistance. As a result, owning to the same system requirements and topology definition the temperature rising of the film capacitor can be validated to be quite lower than electrolytic capacitor involved higher ESR. Thanks to desired lower temperature rising of the film capacitor, so that it will exhibit more excellent performance by means of observing the lifetime vs. temperature curve in figure 4. Besides above consideration as regarding the temperature linking with the lifetime of the film capacitor, which also can be relevant to peak ripple voltage, ripple current, hot spot temperature and in [16] detailed demonstration on lifetime of film capacitor has been verified according to practice experiment in motor drives.

3.3 Power module failure rate

For the power module, many different physical and chemical processes can produce failure due to accelerated temperature stress and temperature cycling, hereby highly accelerated life tests are often employed in reliability prediction approach for the integrated electronic components such as power module.

The Chi^2 distribution is often used in demonstrating the reliability, because it is a probability distribution that relates to the expected values. Generally, the relationship between failure rate and the Chi^2 distribution is as follows:

$$FIT_{LCL} = \frac{\chi^2_{1-\alpha,2F+2}}{2 \times N \times t \times AF} \times 10^9 \quad (5)$$

LCL: lower confidence level; α: *LCL* value; F: failure samples in tested samples; N: in tested samples; t: weighted average time of operation; AF: acceleration factor shown as below equation shown:

$$AF = \frac{t_1}{t_2} = e^{\frac{E_a}{k}\left(\frac{1}{T+T_a} - \frac{1}{T+T_S}\right)} \quad (6)$$

K: Boltzmann's constant; Ea: activation energy; Ts: stress level of the temperature; Ta: ambient temperature.

In order to calculate the practical failure rate, the relevant parameters have been provided by the manufactures as shown in table III:

Table III: Reliability parameter calculation

Des	Parameter	Defined value of Power Module	Defined value of MOSFETs	Defined value of Diode
Accelerated factor	K	8.6171x 10^{-5}	8.6171x 10^{-5}	8.6171x 10^{-5}
	E_a	1eV	0.7	0.7
	T_s	125°C	90°C	90°C
Failure rate due to temperature	LCL	0.6	0.6	0.6
	F	'0' failure	-	-
	$\chi^2_{1-\alpha,2F+2}$	1.833	-	-
	Nt	12000 hrs	-	-
	λ	-	36	291

Then, according to the temperature record in Kassel/Germany, the temperature cycle percentage was given in Table IV.

Using above given failure prediction formula for power module and defined formula for the hybrid circuit of discrete components in MIL-HDBK-217F [13], the adjusted failure prediction could be provided considering the weighted temperature cycling in the whole year as below sheet. (See table V)

Table IV: Ambient temperature cycle percentage in whole year in Kassel (T_A is daily maximum temperature shift in the year 2003)

Ambient Temperature Range T_A (°C)	Average T_A (°C)	Portion of this section
-5 to 5	0	β_1=4.1%
5 to 15	10	β_2=17.26%
15 to 25	20	β_3=14.25%
25 to 35	30	β_4=20.55%
35 to 45	40	β_5=30.14%
45 to 55	50	β_6=13.7%

Table V: Failure rate of the power module (PM) and discrete components at different temperature point definition

λ_i @ Temperature		λ_1 @0°C	λ_2 @10°C	λ_3 @20°C	λ_4 @30°C	λ_5 @40°C	λ_6 @50°C
Failure Rate of PM per 10^{10} Hrs		2.14	9.59	38.9	143.7	488	1539
Failure Rate of Hybrid circuit per 10^6 Hrs	6 MOS	1.35	3.86	10	26	60	135
	6 Diode	11	31	83	210	490	1090

Therefore, in the whole year actual solution for the weighted prediction model of the power module and discrete components would be defined as following (See table VI):

Table VI: Weighted calculation sheet

$$\lambda_{ave} = \sum_{i=1}^{6} \lambda_i \times \beta_i \times 10^{-4} \text{ per } 10^6 \text{ hrs}$$

$\lambda_{ave-6MOS}$	$\lambda_{ave-6Diode}$	λ_{PM}
0.00442	0.0375	0.0395

Following, based on the definition in MIL-HDBK-217F the failure rate of the hybrid circuit shall be found out when the discrete components are used for building the inverter bridge (π_E=0.5, π_F=21, π_Q=3.1, π_L=1, [13]).

$$\lambda_{hybrid} = [\lambda_{6MOS} + \lambda_{6Diode}] \times [1 + 0.2\pi_E] \times \pi_F \pi_Q \pi_L$$
$$= 10^{-6} \times [0.00442 + 0.0357] \times [1 + 0.2 \times 0.5] \times 21 \times 3.1 \times 1 \quad (7)$$
$$= 2.873 \text{ per } 10^6 \text{ hrs}$$

$$\lambda_{PM} = 0.0395 \text{ per } 10^6 \text{ hrs} \quad (8)$$

Finally, MTBF of above mentioned two different models are as below equation shown:

$$MTBF_{hybrid} = \frac{1}{\lambda_{hybrid}} = \frac{1}{2.873 \times 10^{-6}} = 0.348 \times 10^6 \text{Hrs} = 40 \text{ years} \quad (9)$$

$$MTBF_{PM} = \frac{1}{\lambda_{discr}} = \frac{1}{0.0395 \times 10^{-6}} = 25.32 \times 10^6 \text{Hrs} = 2890 \text{ years} \quad (10)$$

From the above given calculation results, it has shown that power module could contribute better performance for the system reliability. Additionally, favorable thermal design by tightly contact between the

chips and the substrate, excellent bond and trace layout with advantageous installation interface which will further optimize and reform the reliability of the power module and MIC. Therefore, technical power module supplied from the manufacture is recommended for the inverter application.

3.4 System reliability prediction

In order to achieve the high reliability of the MIC system, film capacitor and special designed power module including 6 CoolMOS + 6 SiC diodes investigated technically by Infineon are selected for the system design in view of the excellent electric performance and reliability demonstration.

In order to predict the reliability of the MIC system, MIL-HDBK-217F [13]; Bellcore TR-332 [17] and IEC 62380 [18] are recommended for the calculation comparison as regarding the typical components selection and practical operation temperature. For the reliability prediction, the operation temperature of the electronic component is an important influence factor, and 60° operation temperature and 4642 operating hours in the whole year are supposed.

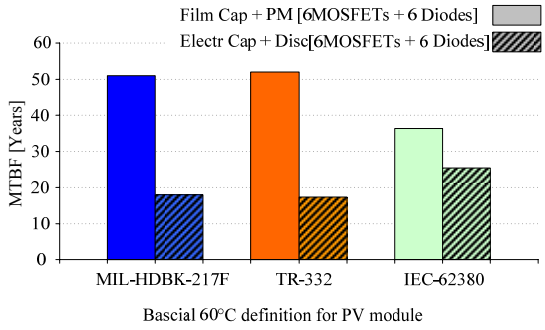


Figure 5: MTBF comparison using MIL-HDBK-217F, TR-332 and IEC 62380

All above mentioned prediction models are often used for the reliability prediction of the commercial product. No matter what kind of prediction model will be employed, $MTBF_{min}$=37 years could be observed in the histogram. Besides, the average temperature of the PV module located in Kassel is T_{avg}=24.1°C [19]. Thus, according to the 10°C rule in reliability prediction: every 10°C decreasing will lead to the twice MTBF increasing, and therefore $MTBF_{avg\ (min)}$ >200 years.

4 THERMAL SIMULATION

For the reliability prediction, besides the voltage stress and vibration, the temperature factor is one quite important influence factor to analyze the product reliability in deep. Using the different prediction models, and definition of the temperature factor also will be different, the following figure 6 gives the comparative at temperature factor for 3 different prediction models.

Observing the figure 6, once the operation temperature exceeds 60°C, IEC 62380 will bring out prominent influence for the reliability prediction. In figure 5, this conclusion is also obvious when the recommended components are employed for MIC. Even though using IEC-62380 prediction model will contribute relative higher negative effectiveness for the reliability, the prediction results showed that minimal MTBF can be up to 200 years defined using 24.1°C average operation temperature in Kassel/Germany.

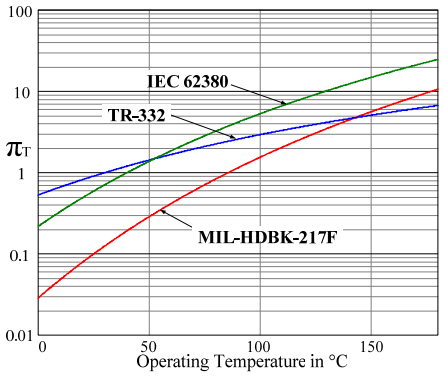


Figure 6: Comparison of the temperature dependence

Regarding to the operation temperature of the MIC which must be installed tightly insulated on the back side of the PV module and could cause high temperature transmission coming from PV module, thus next description will be focused on the thermal simulation taking into account authentic operation environment in order to give the comparison between the calculation and the simulation under the supposed operation condition.

For the thermal simulation, FEMlab is used to simulate the thermal behavior. In order to simplify the modeling proceeding, the system will be segmented into: Power Module, Power supply, Inductive devices, microcontroller and other function blocks.

4.1 Thermal simulation with integrated PV module

The original concept of the MIC is to integrate the 3 phase inverter to the PV module which will be called AC module. Hereby, the inner temperature of the design housing will be affected directly by the surface temperature of the PV module. Based on mentioned point, the thermal model will be built considering the integration between the inverter and the PV Module.

According to the power dissipation of the different electronic components and implementation function, and meanwhile on account of the limitation of the algorithm and simulation platform, the modeling has been simplified only including several critical components section and the same loss performance of the components is combined or divided into a few symbol models.

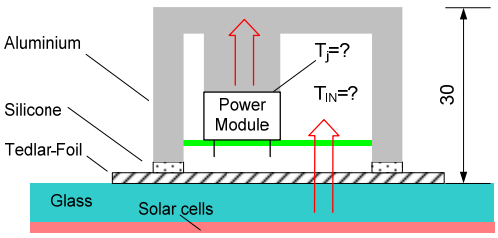


Figure 7: Housing design of the MIC special for power module

Because insulation bonded is pasted to prevent the mutual influence between Aluminum housing and the PV

module, during dealing with the models the different mediums are defined such as enclosure Aluminum housing, protection glass of the PV module and the outside environment. In order to perform the obstacle for the heat transmission between the PV module and the metal enclosure, Tedlar-foil is adhibited on the surface of the PV module to isolate the thermal transmission. Actual AC module configuration of the MIC is given as figure 7 shown [19].

The advantage of recommended thermal configuration is via making use of the lower thermal impendence and large contact area to remove the power dissipation of the power module and to short heat transmission from the PV module, and thereby to decrease the thermal stress of the enclosure inverter as a result of improving the inverter reliability under high temperature operation condition.

Based on the accurate size definition of the MIC, and simplified consideration for the modeling, 3D thermal simulation could be realized by using FEMlab software (See figure 8)

In figure 8, typical components have been given such as Power Module, Aluminum housing and PV module which have been marked.

In order to let the thermal simulation having the same comparison level with the system reliability prediction based on the 60°C definition for PV module, and hereby surface temperature of the PV module is supposed to be as 60°C. At the same time, all crucial components have been located on identical location with actual prototype design. Some other subordinate components have been integrated one complete function block in order to simplify the simulation configuration.

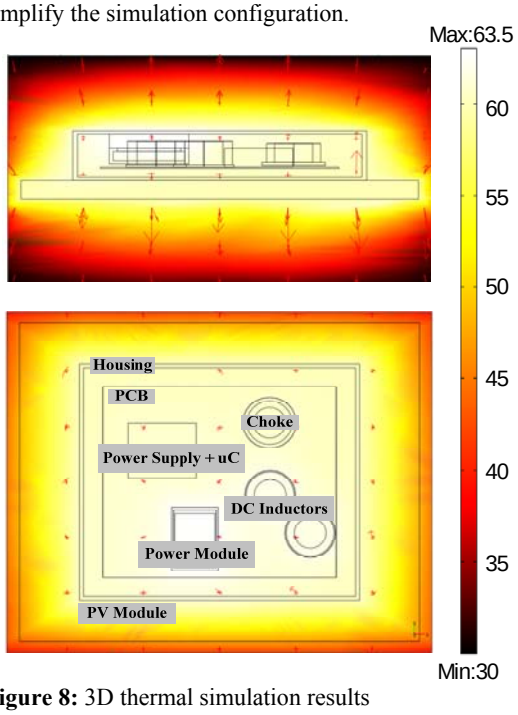


Figure 8: 3D thermal simulation results

From the figure 8 the arrows can be observed obviously, despite of including the additional thermal insulation between the aluminum housing and the PV module, partial thermal energy from the bottom of the PV module could be transferred to the MIC.

According to the thermal simulation results, the maximum temperature of the power module is approximately 63.5°C at steady state. 4°C difference between the PV module and the power module verified that the recommended housing design can effectively removal the over heat source generated by power module, and further to be in case of the serious hotspot between the PV module and the inverter which will improve the performance ratio of the PV module and keep the favorable output characteristic after a long period operation.

In order to qualify the simulation model, the AC module has been put into practical field test with temperature monitoring for the PV module and the power module. Figure 9 shows the thermal behavior of the MIC system in the practical field test.

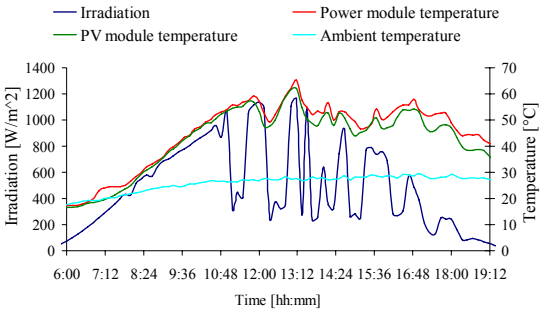


Figure 9: Thermal behavior of the AC module in practical field test

This simulation and the field test showed that the mutual temperature influence of the MIC system could be improved and balanced evidently through adopting the high reliability electronic components and in virtue of optimized housing structure.

5 CONCLUSIONS

Inverters integrated with PV module have to be operated under harsh conditions for a long duration. Some investigations on grid-tied inverter for PV system have been done for discovering the reliability of the modern inverter through performed field test [20]. In this paper, more detail reliability issues of the MIC have been distinguished considering some critical mutual factors such as system structure, components selection and thermal management.

Within the project an actual inverter prototype for performing module integration has been put into operation in field test. Under the critical weather condition, even though the surface temperature of the PV module is up to 60°C, the enclosure 3 phase inverter could still be on the normal operation equipped with the temperature sensor which showed maximal 65°C matching with the simulated thermal behavior on the surface of the power module.

Therefore, through the initial investigation in this paper, the major target which could be achieved is the reliable and efficient integration of the power electronic converter into the PV modules. If this long lifetime combined with an attractive market price is reached, AC modules are quite interesting for the global grid connected PV market in the future.

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