Científica Vol. 12 Núm. 3 pp. 149-155
© 2008 ESIME-IPN. *ISSN 1665-0654.* Impreso en México

Reliability Analysis of the Power-Electronics Stages in Grid-Connected PV Systems

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Recibido el 3 de julio de 2007; aceptado el 19 de febrero de 2008.

1. Abstract

This paper presents the reliability analysis of the power-electronics circuits in three grid-connected photovoltaic systems. The analysis is mainly aimed at verifying the mean time between failures achieved, and is performed according to the procedure outlined in the MIL HDBK 217F. The circuits analyzed are an integrated topology, a two-stage configuration, and a three-stage one, all commutating in the hard-switching mode. The most failure-prone components, and the stress factors with the highest contribution to the failure rate are identified. It was found that the MOSFETs are the weakest link, and that the dominant stress factor is related to temperature. Reliability can be improved if the switching devices are overrated; however, using too large devices can be counterproductive.

Key words: pulse compression, synthetic aperture radar (SAR), atomic functions, windowing.

2. Resumen (Análisis de la confiabilidad de convertidores de potencia en sistemas fotovoltaicos interconectados a la red eléctrica)

Este artículo presenta un análisis de la confiabilidad en los circuitos electrónicos de potencia de tres sistemas fotovoltaicos interconectados a la red eléctrica. El análisis se enfoca principalmente a la verificación del tiempo medio de fallas, y se realiza mediante el procedimiento establecido en el estándar militar MIL-HDBK 217F. Los circuitos analizados son: una topología integrada, una configuración de dos etapas y una configuración de tres etapas, todas ellas en modo de conmutación dura. Se identificaron los componentes más propensos a fallar y los factores de esfuerzo que mayor contribución tienen sobre la tasa de fallo. Se determinó que los transistores MOSFET son los elementos con menor confiabilidad y que el factor de ajuste dominante es el relacionado con la temperatura. La confiabilidad puede mejorarse sobredimensionando la capacidad de los dispositivos de conmutación; sin embargo, el uso de dispositivos excesivamente sobredimensionados puede resultar contra-producente.

Palabras clave: conversión de energía, electrónica de potencia, confiabilidad.

3. Introduction

The current trend in photovoltaic (PV) systems for residential applications is toward grid-connected apparatus, with powers between 1 kW and 5 kW. In these applications, a major issue is the maintenance cost, which is directly related to reliability. In a typical system, the PV cells have an operational life in excess of 20 years. The power stage, however, usually has a much shorter operational life. There have been several programs aimed at increasing the installation of distributed energy resources. A large number of PV systems has been fielded, and reliability data has been collected throughout the world. The International Energy Agency reported that 98% of the failures were related to the power stage, and the average time to failure was about 5 years. Similar results were obtained in the German "1000 Roofs" program, and in the Japanese "Residential Japan" program [1].

The great majority of electronic components do not have any mechanism that will cause degradation or failure during storage or use, provided that they are properly selected and applied (in terms of performance, stress and protection), not defective or damaged when assembled into the circuit, and not overstressed or damaged in use [2]-[4]. Nevertheless, electrolytic capacitors have been singled out as the most troublesome component, and topologies without large capacitors have been developed [5]-[7]. It is assumed that the avoidance of electrolytic capacitors provides, by itself, a higher reliability, regardless of the total number of components employed, the switching modes, and the stresses.

The power stage in a PV system can be built in a number of ways, and several surveys of single-phase inverters aimed at residential installations have been reported recently [8], [9]. The surveys, however, are mainly concerned with the topologies from a power-electronics point of view, and do not explicitly take into account the reliability. Only one survey attempts to describe this subject, albeit in an incomplete manner, establishing as a guideline the number of active devices in the power stage [10]. The lack of relevance of reliability issues might be due to the fact that the vast majority of the topologies reported where developed with other parameters in mind, such as efficiency, cost or volume.

On the other hand, there is an effort to design and manufacture high reliability inverters, with 10 years mean time between failures [11], [12]. Recently, a methodology to upgrade the power converter reliability has been presented. Several factors (duty cycle limits, isolation requirements, EMI, switching mode, continuous or discontinuous conduction mode, etc.) should be taken into account during the design cycle [13]-[15]. The first step to achieve a high reliability converter is to select a suitable topology.

This paper is a step toward identifying the most reliable topologies for single-phase PV systems. It presents the reliability-based analysis of three hard-switching inverters previously reported: a two-stage PV system, a three-stage one, and an integrated topology. The reliability-related parameters, such as the failure rate, are calculated following the procedure outlined in MIL-HDBK 217 [16]. A comparison between the topologies is performed, and both the components, and the stress factor with the highest contribution to the failure rate are identified.

4. Background

The MIL-HDBK 217 handbook lists the failures rates λ_b for electronic devices. To predict the reliability of an electronic assembly it is necessary to first calculate the actual failure rates λ_b of the components involved. The actual values are obtained multiplying the listed λ_b values by the π factors that take into account the stresses. The actual failure rate is given by:

$$\lambda_p = \lambda_b \left(\prod_{i=1}^{n} \pi_i \right) \tag{1}$$

where n is the number of factors for each device. The mean time between failures MTBF is given by:

$$MTBF = \lambda_p^{-1} \tag{2}$$

The reliability R can be calculated as:

$$R = e^{-\lambda pt} \tag{3}$$

Table 1. Stress factors.

Device	π_T	π_Q	π_E	π_A	π_C	π_V	π_S
Inductor	•	•	•				
Transistor	•	•	•	•			
Capacitor	•	•	•		•	•	
Diode	•	•	•				•

Unless some kind of redundancy is included, the reliability R_p of the power stage in a PV system (of m items) is calculated as:

$$R_p = 1 - \prod_{j=1}^{m} (1 - R_j) \tag{4}$$

where the term R_j corresponds to the individual reliabilities of the components in the power stage. It follows, then, that a soft-switching topology does not necessarily provide a better reliability than a hard-switching approach, particularly if soft-switching is achieved at the expense of a larger number of devices.

Power electronics apparatus are usually built with transistors, diodes, capacitors and inductors. The stress factors for these devices are listed in table 1.

The factor π_T is related to the temperature. It can be calculated with the expressions listed in table 2.

The term T_j is the junction temperature, for transistors and diodes, or the hot-spot temperature for inductors and capacitors. It can be calculated using:

$$T_j = T_c + \theta_{jc} * P_d \tag{5}$$

where T_c is the case temperature, θ_{jc} is the thermal resistance between junction and case (or hot-spot and case), and P_d is the power dissipated by the device.

Table 2. Temperature stress factors.

Inductor	$\pi_T = e^{\left[-1925\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right]}$
Transistor	$\pi_T = e^{\left[-\frac{0.35}{8.617 \times 10^{-5}}\left(\frac{1}{T+273} - \frac{1}{298}\right)\right]}$
Capacitor	$\pi_T = e^{\left[-3091\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right]}$
Diode	$\pi_T = e^{\left[-\frac{0.11}{8.617 \times 10^{-5}}\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right]}$

Table 3. Quality factors.

Quality	π_Q
JANTXV	0.7
JANTX	1.0
JANT	2.4
Commercial	5.5
Plastic	8.0

The quality factors π_Q are listed in table 3.

The factor π_E depends on the operational environment: ground (*G*), seaborne (*N*), airborne (*A*), Missile (*M*), etc. In this case, it is assumed that the environment is ground benign (G_B), and $\pi_E = 1$.

The application factor π_A basically depends on the power handled by the device, as listed in table 4.

The factor π_C depends on the capacitance value, expressed in microfarads, and according to:

$$\pi_C = C^{0.23} \tag{6}$$

The factor π_V depends on the ratio *S* between the voltage applied to the capacitor, and its rated voltage. This factor is calculated with:

$$\pi_V = (S/0.6)^5 + 1 \tag{7}$$

The factor π_S depends on the ratio V_s between the reverse voltage applied to a diode, and its rated reverse voltage. In can be calculated with:

$$\pi_S = V_S^{2.43} \tag{8}$$

5. Methodology

To perform a fair comparison among the different topologies, they must be designed for the same operating point, and assume that the operating conditions are similar. Thus, all the photovoltaic systems were designed with a 500 VA output rating. The inverters were designed using the equations included in the papers that described its operation or, for well-known configurations, the standard procedures described in text books. Once the values of the passive elements were calculated, similar criteria were applied to select the particular components used in the three designs.

Table 4. Application factor.

Application	π_A
Linear (P_r <2W)	1.5
Small signal	7.0
Power (non linear, P_r >2W)	
2<P_r <5W	2.0
5<P_r <50W	4.0
50<P_r <250W	8.0
P_r >250W	10.0

Once the components types and values are known, the failures rates λ_b can be readily obtained from MIL-HDBK 217, but the stress factor must be calculated for the particular application. These factors depend on the maximum voltages and currents in the components. In turn, these parameters were obtained by simulating the power circuits in SPICE© and PSIM©.

The actual reliability calculations were performed using RELEX© [17], a commercial software package that includes a database with the component failure rates, and executes the procedure in MIL-HDBK 217. It calculates the stress factors when maximum voltage, current, and power dissipation for each component are provided. It also calculates and plots reliability parameters, such as failure rate or MTBF, and its behavior over temperature or time. It should be noted that the calculations only included the elements in the power stage. The control circuitry and other elements, such as the transistor drivers, were not included in the analysis.

6. Reliability calculations

6.1. Two-stage PV system

The two-stage configuration is shown in Fig. 1. The first stage is an interleaved boost converter that draws a low-ripple current from the DC source. The second stage is a single-phase bridge inverter. The system specifications are as follows: $f_{S(boost)}$ = 75 kHz; $f_{S(inverter)}$ = 5 kHz; V_{IN} =170 V; V_{ca} = 220 V @ 60 Hz; T_1–T_2 = SPP04N50C3; D_1–D_2 = 15ETX06; L_1–L_2 = 6.93 mH; C = 1.096 µF @ 400 V (polypropylene, metalized film. The stress factors are calculated according with the procedures already described. The results are shown in table 5.

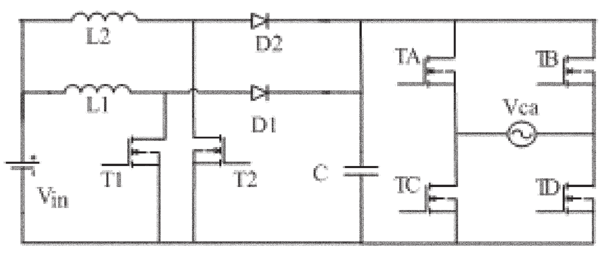

Fig. 1. Two-stages PV system.

Table 5. Stress factor.

	Transistor			
	Boost	**Inverter**	**Diode**	**Capacitor**
λ_b	0.012	0.012	0.25	0.00012
π_A	8.000	8.000		
π_E	1.000	1.000	1.00	1.00000
π_Q	8.000	8.000	8.00	10.00000
π_T	3.760	3.240	3.24	13.36000
π_S				
π_C				1.93000
π_V				9.33000
λ_p	2.890	2.480	2.48	0.28000
T (°C)	102.000	91.300	91.30	95.00000

With these data it is possible to compute the reliability parameters. Fig. 2 shows the percentage contributions from the individual components to the overall failure rate. Fig. 3 shows the reliability over time for the overall PV system and the individual contributions from each stage at an ambient temperature equal to 55 °C. Clearly, the most failure-prone devices are the power transistors. The failure rate of the inverter stage is higher than that of the boost converter (59% vs. 41%). This behavior occurs because the inverter includes twice the number of MOSFETs than the boost converter.

It can be seen in table 5 that the highest contribution to the failure rate is due to π_T, which is related to the temperature. In turn, this factor is depends on the power dissipated by the transistors. It makes sense, then, to reduce the dissipation in order to increase the reliability. One way to achieve this reduction is by using transistors with a lower on-resistance R_{ON}. Fig. 4 shows the failure rates associated with the MOSFETs in the inverter stage when the PV system is built with different transistors belonging to the same family, but with increasingly higher current ratings: 4.5A, 8A, 12A, 16A and 21A (from left to right). All transistors are in the TO220 package, regardless of the current rating.

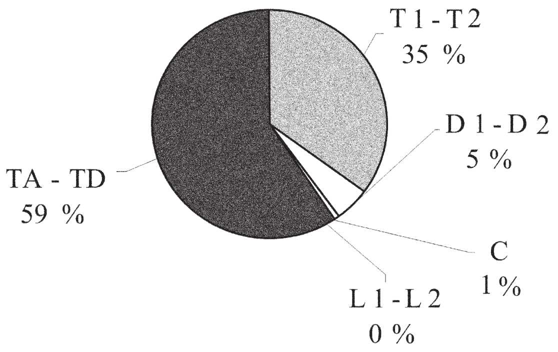

Fig. 2. Percentage contributions from the individual components to the overall failure rate.

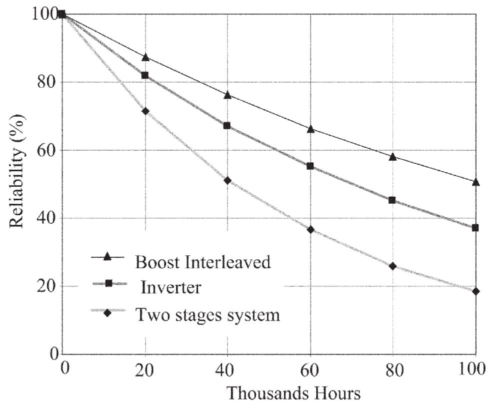

Fig. 3. Reliability results.

It can be notice that increasing the current rating, from 4A up to 16A, provides a 6% maximum reduction in the failure rate. A further increment in the current rating, to 21A, does not translate into higher reliability. The reason is that, although the conduction losses are smaller, the losses associated to gate drive increase because there is a larger C_{ISS}.

Another factor with a high contribution to the failure rate is π_Q. This factor can be improved by using better quality

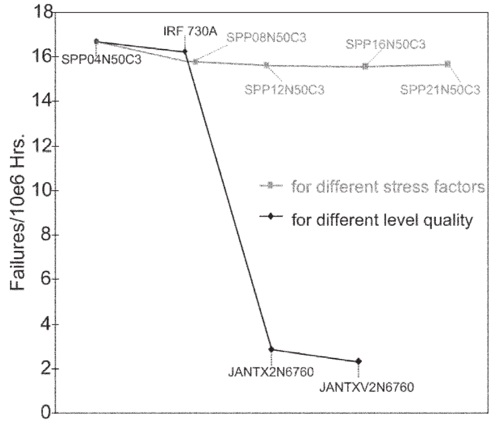

Fig. 4. Failure rates for different stress factors and level quality.

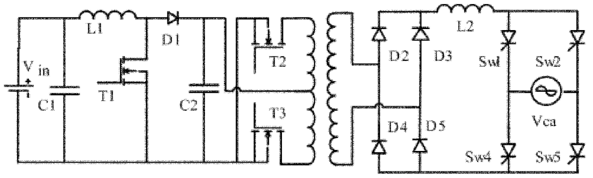

Fig. 5. Three-stages PV system.

components. Fig. 4 also shows the failure rates attained with different quality transistors. The SPP04N50C3 and the IRF730A are commercial quality devices in a TO-220 package. The JANTX2N6760 and the JANTXV2N6760 are high quality devices in a TO-3 package. The four transistors share similar ratings: $V_{DS} = 400V, I_D = 5A, R_{ON} = 1\ \Omega$.

6.2. Three stages PV systems

The three-stage PV system is shown in Fig. 5 [18]. The first stage is a boost DC/DC converter. The second stage is a push-pull DC/DC converter that generates a full-wave rectified voltage. The third stage is a bridge inverter that behaves as a polarity inverter, switching at the mains frequency. The system specifications are as follows: $f_S = 100$ kHz; $V_{IN} = 170$ V; $V_{CA} = 220$ V @ 50 Hz; T1 = IRFP254; T2-T3 = IRFP460; D_1 = BYV29400; D_2–D_5 = BYR29800; SW1-SW4 = BT152800; L_1 = 68μH, RM10; L_2 = 4mH, E42/15; C1 = 3.3μF @ 250V, polypropylene, metalized film; C_2 = 550μF @ 380V, electrolytic, aluminum.

The push-pull converter exhibits the highest failure rate (70%) because it includes two MOSFETs. The inverter exhibits the lowest failure rate (2%), although it includes four switching devices. These devices are thyristors, which are a very mature technology, and therefore have a much higher reliability than MOSFETs. Fig. 6 illustrates the reliability over time at an ambient temperature equal to 55 °C.

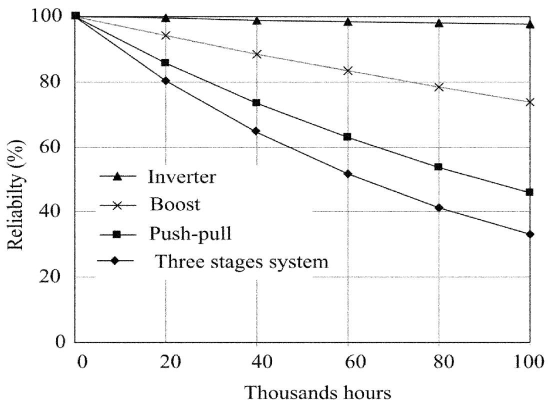

Fig. 6. Reliability results.

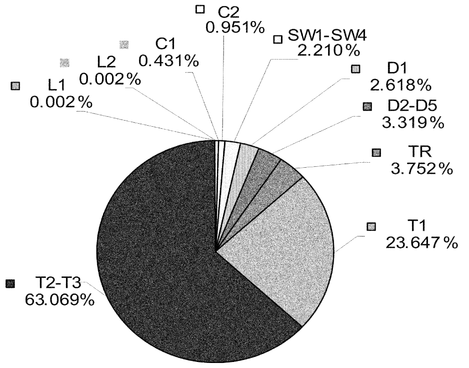

Fig. 7. Percentage contributions from the individual components to the overall failure rate.

Fig. 7 illustrates the percentage contributions from the individual components to the overall failure rate. In this configuration, the inductors contribution to the failure rate is too small to be noticeable. Also, and as in the previous case, the transistors have the lowest reliability. The system includes an electrolytic capacitor at the PV panel terminals. Since capacitors have often been blamed as a major failure source, it is instructive to explore the effect of this element on the overall reliability. Looking at the stress factors for this case, the highest contribution is due to π_V, which is related to the voltage rating. The effect is illustrated in Fig. 8, which corresponds to the overall failure rate, for three different voltage ratings, at $T_A = 55$ °C.

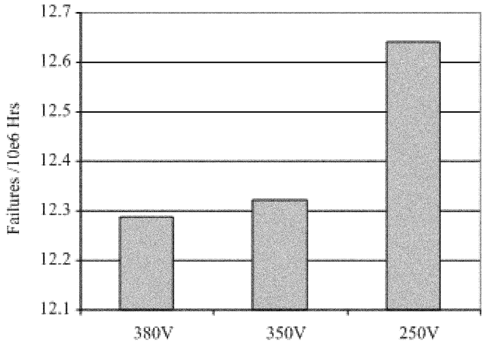

Fig. 8. Overall failure rate for different capacitor voltage rating.

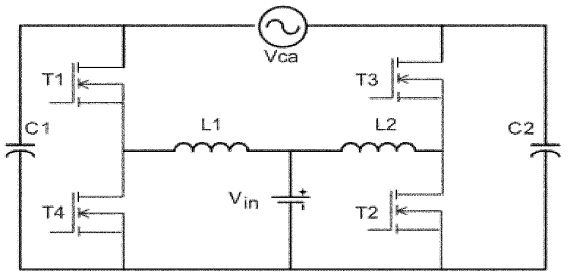

Fig. 9. Boost inverter.

6.3. Boost inverter

An integrated boost inverter [19] is shown in Fig. 9. This is a symmetrical circuit formed by two bi-directional DC/DC converters. Each one generates a DC output, plus an alternating voltage at the mains frequency, and 180° out of phase from each other. The output is obtained in a differential manner, between the outputs, and each converter provides half the output power. The system specifications are as follows: $P_O = 500$W, $f_S = 30$ kHz, $V_{IN} = 48$ V, $V_{CA} = 220$ V @ 60 Hz. T1-T4 = SPP08N50C3; L1-L2 = 424.25 µH; C1-C2 = 17.58 µF @ 250 V (electrolytic, aluminum).

6.4. PV systems comparison

Looking at the failure rates contributions, it is found that the transistors are, by far, the most failure-prone devices (96%). Fig. 10 illustrates the relationship between the reliability and the time, at different ambient temperatures. It can be readily confirmed that the reliability is highly dependent on temperature.

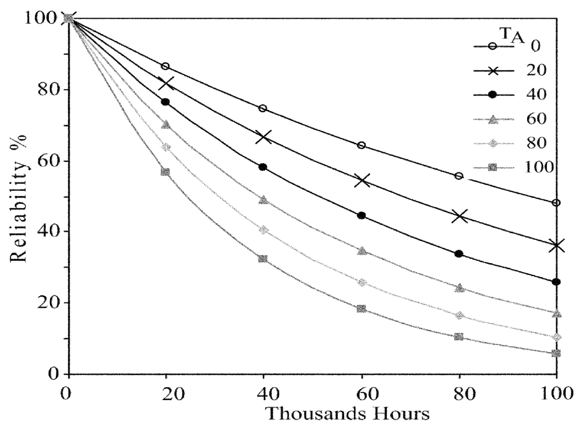

Fig. 10. Reliability results for the boost inverter.

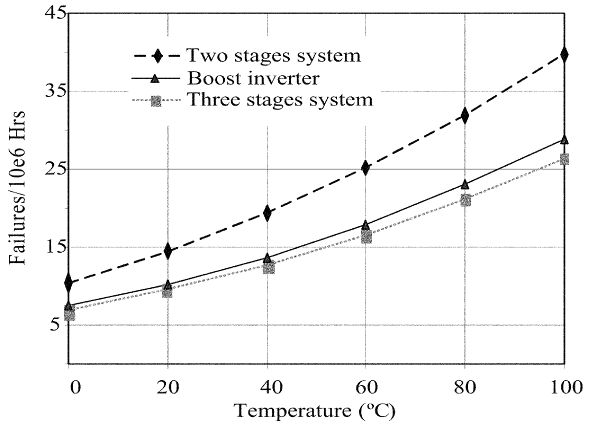

Fig. 11. Failure rate over temperature for the three systems.

Fig. 11 shows the failure rates over temperature for the three PV systems analyzed. Fig. 12 corresponds to the MTBF over temperature. It can be seen that the two-stage configuration has the highest failure rate. This behavior occurs because this topology includes six MOSFETs, with fairly high stresses, while the other configurations include fewer transistors. The most complex configuration is the three-stage one; nevertheless, it exhibits the best failure rate. This can be explained by two reasons. The first one is that the circuit was simulated with the devices listed in the reference where it is reported, and the transistors are overrated. The second reason is that the third

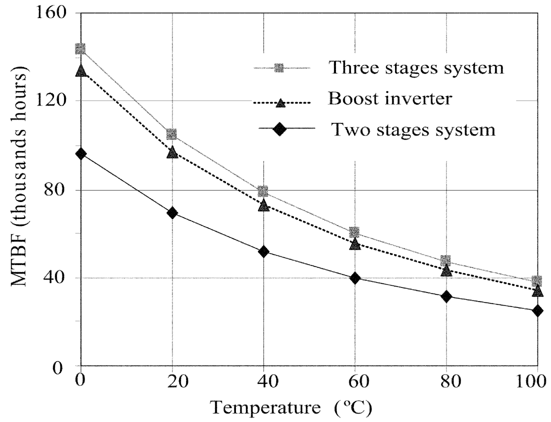

Fig. 12. MTBF over temperature for the three systems.

stage is implemented with thyristors, switching at a very low frequency; therefore, this stage has a high reliability.

For temperatures above 60-70C, some topologies could have MTBFs lower than 40,000 hours (about 5 years). This is an important issue to ponder when the PV system is to be installed in hot weather areas.

7. Conclusions

Analyzing the results obtained, the following conclusions can be drawn.

- The complexity of the circuit, in terms of the number of devices, is not necessarily related to the reliability, although it might become important when some other issues, such as the efficiency or volume, are taken into account.
- The capacitor is not necessarily the weakest link in the circuit. In the three circuits analyzed, the switching transistors were the weakest link. Other components, such as the inductors, do not contribute significantly to the failure rate.
- The stress factor with the highest contribution to the failure rate is π_T. Therefore, the thermal design is a critical issue and must be carefully performed. Overrating the transistors might help increase the reliability, but only to a certain point. As illustrated by figure 4, using too large transistors can be counterproductive. This is particularly true when high frequency switching is used.
- The capacitors contribution to the failure rate was quite small. Nevertheless, some improvements can be obtained by using capacitors with a higher voltage rating. Also, to avoid overheating it is of paramount importance to use low ESR capacitors.
- Reliability can be compromised when the design is dictated by parameters such as volume, usually involving higher frequency switching, and corresponding higher losses.

It should be noted that the conclusions apply only to the configurations analyzed, the three operating in hard-switching mode. It remains to investigate the reliability behavior of soft-switching configurations, and other, more complex topologies such as multilevel inverters, that have already been proposed for single -phase grid connected PV systems. In any case, identifying the stress factors with the highest contribution to the failure rate, will always help improve the overall reliability.

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Dentro del artículo la numeración comienza a partir del 'Resumen' o el 'Abstract', según sea el caso. Ésta continúa de acuerdo a los siguientes elementos: 1. Resumen, 2. Abstract, 3. Introducción, 4. Desarrollo, 5. Conclusiones y 6. Referencias.

Título

El título debe ser lo más corto posible (sin utilizar abreviaciones de preferencia) y no exceder de tres líneas.

Datos del autor

Éstos muestran el o los nombres de los autores, la dirección de la institución a la cual pertenecen, el teléfono, fax y correo electrónico.

Resumen

Debe contener 200 palabras como máximo. Consiste en una pequeña descripción de la investigación y una breve información de los resultados del trabajo que permite a los lectores identificar con rapidez los aspectos fundamentales del artículo y discernir la relevancia de éste.

Abstract

Se incluye un resumen en inglés si el artículo está en español o viceversa. Éste aparece inmediatamente después del resumen en inglés o español, según sea el caso.

Introducción

Expresa los antecedentes, límites, alcances y relevancia del problema. Plantea las premisas del mismo, y expresa el objetivo del trabajo. Se sugiere no extenderla como si fuera una exposición analítica.

Desarrollo

Se refiere al desarrollo del tema que puede ser teórico, experimental, teórico-experimental o la descripción de un nuevo diseño. Es la parte medular y está compuesta por el planteamiento del problema y análisis del mismo, mencionando los materiales, métodos y técnicas. Las subdivisiones de este apartado se dejan al criterio del autor.

Conclusiones

Establece la respuesta global del problema, son los objetivos alcanzados, las hipótesis comprobadas, modificadas o rechazadas.

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Es la lista de fuentes bibliográficas: libros, artículos, manuales, memorias, etcétera. Deben aparecer en el orden en el cual se mencionan dentro del artículo con las siguientes especificaciones:

Libros:

[1] Autor, *Título*, número de edición, Editorial, Ciudad, año de publicación.

[2] Autor, 'Capítulo del libro', *Título*, número de edición, Editorial, Ciudad, año de publicación, páginas.

Ejemplo:

[1] Kays,W.M. & Crawford, M.E., *Convection Heat and Mass Transfer*, 2ª ed., McGraw-Hill, New York, 1993.

Revistas:

[1] Autor, «Título del artículo», *Revista*, **volumen** (número), año, páginas.

Ejemplo:

[1] Lara, J.C., Hernández, D.G. y Alonso-Vanegas, MA., «Desarrollo de un aparato estereotáctico con arco centrado», *Arch Neurocien.* **10**(3), 2005, pp. 196-202.

Anexos

Los agradecimientos, simbología, notación y otros anexos, se consideran dentro del cuerpo del artículo y se dejan a consideración del autor. Se debe indicar si el trabajo ha sido previamente presentado en alguna institución científica o realizado con la ayuda de una subvención o fondo especial.

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Para obtener la mejor calidad al realizar la edición de los manuscritos en el formato de la revista, se recomienda que: *a*) el texto se capture en un procesador de textos (*word*); *b*) el tipo de letra del texto sea *Times* de 10 puntos, en una página con márgenes superior e inferior y derecho de 2.5 cm, margen izquierdo de 3 cm a dos columnas con espaciamiento de 0.77 cm entre ellas; *c*) las ecuaciones y fórmulas numeradas para mayor claridad, acrónimos y abreviaciones deben definirse la primera vez que sean usados en el texto; *d*) los pies de las figuras deben estar debajo de éstas con la indicación 'Fig. 1'; además, el título de los ejes de las figuras a menudo es causa de confusión, por lo que se sugiere usar palabras en lugar de símbolos. Los encabezados de las tablas deben estar arriba de éstas; *e*) las figuras y tablas en el documento deben entregarse en archivos por separado (.tif, .jpeg), es importante que al pasar cualquier imagen por un escáner debe hacerlo con una resolución de 300 ppp (puntos por pulgada). De antemano gracias.

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