Reliability Analysis for a Waste Heat Recovery Power Electronic Interface Applied at All-Electric Aircrafts

Stefanos Saridakis, Nick Papanikolaou, Dionisios Voglitsis
Department of Electrical & Computer Engineering
Democritus University of Thrace
Xanthi, Greece
npapanik@ee.duth.gr

Eftichios Koutroulis
School of Electronics & Computer Engineering
Technical University of Crete
Chania, Greece
efkout@electronics.tuc.gr

Emmanuel Tatakis, Georgios Christidis, Ioannis Karatzaferis
Department of Electrical & Computer Engineering
University of Patras
Patras, Greece
e.c.tatakis@ece.upatras.gr

***Abstract*— Reliability is one of the most important parameters in aircrafts. In this paper, a method for the calculation of reliability (i.e. number of failures / 10^6 hours) of a three-phase full-bridge inverter, which is employed in the dynamic waste heat recovery system of an aircraft, is presented. The main factors for the reliability analysis that have to be considered is the topology of the inverter, the ambient temperature conditions, the power switches (type and modulation technique), and the harmonic filter. The power inverter reliability has been calculated using a software program developed under the Matlab platform, which was used to calculate the failure rate of each device of the inverter, such as the power switches, the DC-bus capacitor and the filter inductor, given the operating switching frequency value. The results indicate that at higher switching frequency levels the inverter of the DWHR system exhibits a high failure rate, thus resulting in a lower Mean Time Between Failures (MTBF).**

Keywords*— *all-electric aircrafts; dynamic waste heat recovery; inverters; reliability;

I. Introduction

Due to safety requirements, reliability is one of the most important parameters in aircraft electric systems, which in recent years plays an important role because of the regulations that have been established [1]-[2]. The main research effort in this application is currently on improving the reliability of power electronics [3]-[4].

Towards this direction, an important electric power supply that has been recently introduced is the so-called Dynamic Waste Heat Recovery System (DWHR), which constitutes a backup supply while, simultaneously, it achieves a high energy saving ratio [5], [6]. The block diagram of the DWHS system that is incorporated in All-Electric Aircrafts (AEAs) is illustrated in Fig. 1 [5]-[6]. It consists of a hot-air engine, which is fed directly by the kinetic energy of exhaust gases, causing the rotation of a permanent magnet (PM) synchronous generator. The PM synchronous generator is employed, since it provides the advantages of high power density and low maintenance requirements. Thus, the reliability of the overall DWHR system is increased. Due to its high output power, the DWHR system is typically designed to also operate as a standby power generator, which operates in case that the operation of the main generator is suspended (e.g. in case of malfunction). This feature increases the reliability and availability of the overall electric network. The electric energy produced is interfaced to a three-phase inverter through an external filter (i.e. the three phase inductor depicted in Fig. 1), which is connected at the stator windings of the generator. Finally, the inverter manages the regenerated energy amount and feeds it to the 270 V DC bus. The inverter operates at a time-varying power level, depending on the load power consumption, thus it is designed such that it is capable to

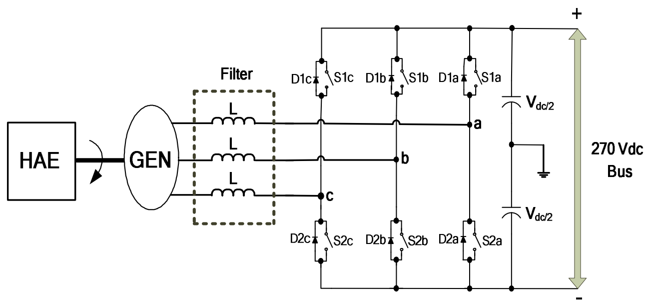

Fig. 1. A block diagram of the aircraft DWHR system.

operate with transient loads.

Several power converter topologies have been proposed in the past, which fulfil the high-reliability requirements of the aircraft DWHR application under study, such as the three

This work was supported by the "Reinforcement program of small and medium enterprises for research and technological development activities" under research project **23SMEs2009** and funded by the European social fund and by national funds.

phase discontinuous conduction mode (DCM) boost rectifier in series with a dc/dc buck converter [7]-[9], the three-phase buck-boost power factor correction (PFC) rectifier [10]-[11], the parallel active filter (PAF) [12] and the three phase buck rectifier in series with a dc/dc boost converter [13]. However, for the specific application under consideration, these converters are less attractive, mainly due to their high cost and circuit complexity [14]. Thus, the three phase full-bridge inverter structure shown in Fig. 1 is mostly suitable for incorporation in the aircraft DWHR system.

Till present, the reliability performance of DWHR systems has not been investigated. This paper presents the detailed model of reliability for each device that composes a three-phase full-bridge inverter for energy recovery in aircrafts, such as the power semiconductors, capacitors, inductors, etc. Then, the failure rate of the overall inverter is evaluated under various operating conditions and power semiconductor types and the corresponding reliability-analysis results are presented.

II. The Proposed Method for Reliability Analysis of the Aircraft DWHR System

A flowchart of the procedure employed to calculate the reliability of the aircraft DWHR system, is depicted in Fig. 2. The failure rate of the individual devices is calculated in accordance with the MIL-HDBK-217F [15], taking into account their technical characteristics, the topology of the power inverter and the associated stress factors which depend on the modulation technique of the power semiconductors, the ambient temperature etc.

The failure rate of the three phase full-bridge inverter (in number of failures / 10^6 hours) is the sum of the failure rate of each device that it comprises and it is given as follows [16]:

$$\lambda_{inv} = 6\lambda_{ps} + 6\lambda_{pd} + 2\lambda_{pc} + 3\lambda_{pi} \tag{1}$$

where, λ_{ps}, λ_{pd} are the failure rates of the power switches and diodes of the converter, respectively, λ_{pc} is the failure rate of the capacitors in the DC-bus and λ_{pi} is the failure rate of the filter inductor.

The Mean Time Between Failures MTBF (hours) is calculated using the resulting value of λ_{inv}, according to the following equation:

$$MTBF = \frac{1}{\lambda_{inv}} = \frac{1}{6\lambda_{ps} + 6\lambda_{pd} + 2\lambda_{pc} + 3\lambda_{pi}} \tag{2}$$

The calculation of the failure rates of all components that compose the power inverter is performed as analyzed in the following sections.

A. Failure Rate for IGBTs

In this paper, the reliability of IGBT devices is calculated based on the MIL-HDBK-217F [15]. According to this, the failure rate of the IGBT devices depends on several factors, such as the junction temperature, the voltage stress, the power rating, the quality of the device, and the environmental operating conditions. The IGBT failure rate model which has been used is given by [2]:

$$\lambda_{ps} = \lambda_{b,ps}\pi_\tau \pi_a \pi_\rho \pi_s \pi_q \pi_e \tag{3}$$

where $\lambda_{b,ps}$ is the base failure rate of the IGBT device and π_τ is the junction temperature factor.

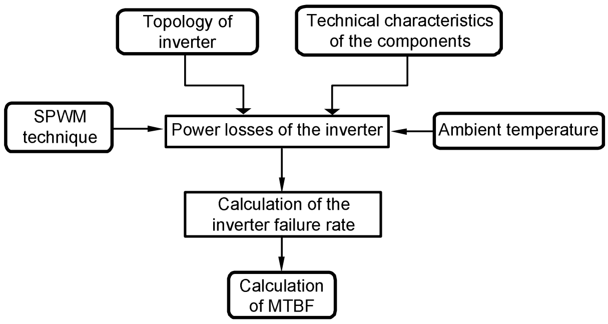

Fig. 2. A flowchart of the proposed method for performing the reliability analysis of the aircraft DWHR system.

The value of π_τ is calculated as follows:

$$\pi_\tau = \exp\left[-2114 \times \left(\frac{1}{T_{j,ps} + 273} - \frac{1}{298}\right)\right] \tag{4}$$

where π_a, π_p, π_s, π_q, π_e, are the application type factor, the power rating factor, the voltage stress factor, the quality factor and the environmental factor, respectively, for IGBT power switches [15], [17]. The factor values in (4) according to MIL-HDBK-217F are presented in Table I.

Table I. The values of the reliability factors (MIL-HDBK-217F)

		π_a	π_p	π_s	π_q	π_e	π_{cv}
Device	IGBT	0.7	1	0.11	1	13	-
	Diode	-	-	0.054	1	13	-
	Capacitor	-	-	-	3	12	0.55
	Inductor	-	-	-	3	6	-

The junction temperature of the IGBT power semiconductor in (4) is given by the following equation [18]:

$$T_{j,ps} = T_a + \theta_{jc,ps}P_{ps} + \theta_{ca}P_{tot} \tag{5}$$

where T_α (^oC) is the ambient temperature $\theta_{jc,ps}$ and $\theta_{c\alpha}$ ($^oC/W$) are the thermal resistances from the junction to the case of the IGBT device and of the heat sink, respectively, P_{ps} and P_{tot} (*W*) are the power losses (conduction and switching) of an individual IGBT device and of all power semiconductors (including both IGBTs and freewheeling diodes) which are mounted on the same heat sink, respectively.

In the proposed method of reliability calculation, the junction temperature of the IGBT $T_{j,ps}$ in (5) should be subject to the following constraint:

$$T_{j,ps} \le T_{j,ps,\max} \tag{6}$$

where $T_{j,ps,max}$ is the maximum junction temperature of the IGBT switch, which is specified in the manufacturer datasheet.

B. Failure Rate for Diodes

Similarly to the IGBT power switches, the failure rate of power diodes also depends on several factors that play an important role in their reliability performance. For the power diodes, the failure rate model used is the following:

$$\lambda_{pd} = \lambda_{b,pd}\pi_{\tau}\pi_{s}\pi_{q}\pi_{e} \quad (7)$$

where $\lambda_{b,pd}$ is the base failure rate of the diode [15]. The factor values in (7) according to MIL-HDBK-217F are tubulated in Table I.

The value of π_{τ} is calculated as follows:

$$\pi_{\tau} = \exp\left[-3091\times\left(\frac{1}{T_{j,pd}+273}-\frac{1}{298}\right)\right] \quad (8)$$

The junction temperature of the diode $T_{j,pd}$ in (8) is given by the following equation [16]:

$$T_{j,pd} = T_a + \theta_{jc,pd}P_{pd} + \theta_{ca}P_{tot} \quad (9)$$

where $\theta_{jc,pd}$ ($^oC/W$) is the thermal resistance from the junction to the case of the diode and P_{pd} (W) are the power losses (conduction and switching) of the diode.

$T_{j,pd}$ should be subject to the following constraint:

$$T_{j,pd} \le T_{j,pd,\max} \quad (10)$$

where $T_{j,pd,max}$ is the maximum permissible junction temperature for the diode, specified in the manufacturer datasheet.

C. Failure Rate for DC-bus Capacitor

The DC-bus capacitors constitute the weakest device in applications of power inverters, since they are sensitive to the applied voltage stress and operating temperature. The capacitor failure rate model, which has been employed in the proposed method, is given by [15]:

$$\lambda_{pc} = \lambda_{bc}\pi_{cv}\pi_{q}\pi_{e} \quad (11)$$

where π_{cv} is the capacitance factor. The factor values in (11) according to MIL-HDBK-217F are shown in Table I.

The base failure rate of the capacitor, λ_{bc}, in (11) is a function of ambient temperature, T_a, and operating voltage of the capacitor, according to the following equation:

$$\lambda_{bc} = 0.0028\times\left[\left(\frac{S_c}{0.55}\right)^3+1\right]\times\exp\left[4.09\times\left(\frac{T_a+273}{273+T_{rated}}\right)^{5.9}\right] \quad (12)$$

where $S_c = V_{dc}/V_{rated}$ is the voltage stress ratio, V_{dc} is the voltage of the DC-bus, V_{rated} is the rated operating voltage of the capacitor and T_{rated} is the rated operating temperature of the DC-bus capacitor under consideration.

D. Failure Rate for Filter Inductor

The inductors generally exhibit high reliability, but the usual cause of their failure is primarily the deterioration of the winding insulation. This is due to the current stresses arising from the voltage amplitude (e.g. Pulse Width Modulated - PWM), as well as from high temperature operation [17]. The failure rate of an inductor is given by [15]:

$$\lambda_{pi} = \lambda_{bi}\pi_{\tau i}\pi_{q}\pi_{e} \quad (13)$$

where λ_{bi} is the base failure rate of the inductor. The factor values in (13) according to MIL-HDBK-217F are shown in Table I.

The value of the inductor temperature factor, $\pi_{\tau i}$, is calculated using the following equation:

$$\pi_{\tau i} = \exp\left[-\frac{0.11}{8.617\cdot 10^{-5}}\left(\frac{1}{T_{HS}+273}-\frac{1}{298}\right)\right] \quad (14)$$

In (14) the hot spot temperature of the filter inductor, T_{HS}, is calculated as follows [15]:

$$T_{HS} = T_a + 1.1\cdot 125\cdot W_L / A_S \cdot L\cdot I \quad (15)$$

where $L(H)$ is the inductance value, A_s $[m^2/(H\cdot A)]$ is the radiating surface area of case per unit inductance, $I(A)$ is the output current of the PM generator and $W_L(W)$ is the total copper and core losses of the inductor, which are calculated according to [18].

III. POWER LOSS MODEL OF THE DWHR INVERTER

In the proposed process for calculating the reliability of the DWHR system, the power switches and diodes are modeled as voltage sources, which are connected in series with resistors [18], [19].The conduction power losses of each power switch, $P_{ps}(W)$ and diode, $P_{pd}(W)$, respectively, are given by:

$$P_{ps} = V_{on,s}\cdot I_{avg,s} + R_s\cdot I_{rms,s}^2 \quad (16)$$

$$P_{pd} = V_{on,d}\cdot I_{avg,d} + R_d\cdot I_{rms,d}^2 \quad (17)$$

where $V_{on,s}(V)$, $R_s(\Omega)$ are the ON-state voltage and resistance, respectively, of the IGBT power switch, $V_{on,d}(V)$, $R_d(\Omega)$ are the power diode forward voltage and resistance, respectively, $I_{avg,s}$, $I_{rms,s}$ (A) are the average and RMS values, respectively, of the power switch current and $I_{avg,d}$, $I_{rms,d}$ (A) are the average and RMS values, respectively, of the diode current [18], [19].

The total switching losses of the three-phase full-bridge inverter, $P_{sw}(W)$, are calculated using the following equation [18]-[20]:

$$P_{sw} = \frac{V_{dc}\cdot I\cdot f_s}{\pi\cdot V_t\cdot I_t}\cdot\left[6\cdot\left(E_{on}+E_{off}\right)\right] \quad (18)$$

where $f_s(Hz)$ is the switching frequency, $V_t(V)$, $I_t(A)$ are the test voltage and current values, respectively, which are provided in the devices datasheet and E_{on}, E_{off} $(Joule)$ are the turn-on and turn-off energy, respectively.

The total conduction losses of the three-phase full-bridge inverter, P_{cond}, is equal to the sum of the conduction and switching losses of the power semiconductors (i.e. power switches and diodes), comprising the three-phase inverter, which are calculated using (16)-(17):

$$P_{cond} = 6\cdot\left(V_{on,s}\cdot I_{avg,s} + R_s\cdot I_{rms,s}^2 + V_{on,d}\cdot I_{avg,d} + R_d\cdot I_{rms,d}^2\right) \quad (19)$$

IV. DWHR SYSTEM RELIABILITY ANALYSIS RESULTS

In order to evaluate the reliability of the DWHR system (Fig. 1), the failure rate models described is Section II have been incorporated in a properly developed software program which operates under the Matlab platform. This program calculates the MTBF of each device according to the MIL-HDBK-217F and also taking into account the specifications of the application (system) under study. The specifications of the DWHR system are the following:

- nominal power: $P_{nom} = 30\,kW$,
- nominal voltage: $V_{nom} = 120\,V$,
- fundamental frequency: $f = 2.1\,kHz$,
- DC-bus voltage: $V_{dc} = 270\,V$,
- power factor: $PF = 0.95$,
- ambient temperature: $T_a = 75\,^oC$,
- DC-bus capacitor: $C = 1400\mu F$ and
- filter inductor (per phase): $L = 40\mu H$.

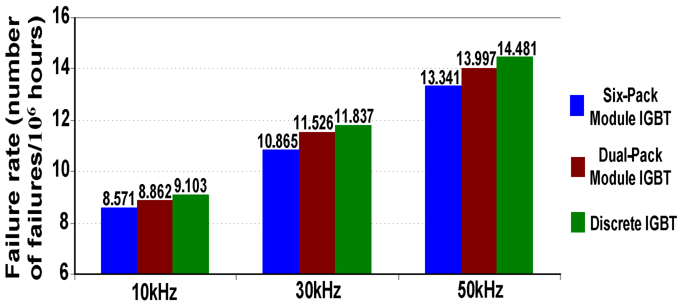

Fig. 3. The total failure rate of the three-phase full-bridge inverter of the DWHR system for different switching frequencies, in case that either a six-pack module, or dual-pack modules, or discrete IGBT power devices are employed.

The reliability performance of the DWHR inverter has been investigated for the cases that it is alternatively built using the IXYS MWI75-12T7T six-pack module, the IXYS MIXA100PF1200TMH dual-pack modules and the IXYS IXDN55N120D1 discrete IGBTs devices, respectively. During the reliability evaluation process of the power inverter of the DWHR system, the switching frequency has been considered to vary in the range of 10 kHz - 50 kHz. This enables to evaluate the reliability of the three-phase full-bridge power inverter in case that either a six-pack module, or three dual-pack modules, or six discrete IGBTs are used and also either they are all mounted on a common heat-sink, or each IGBT power device is mounted on a separate heat sink.

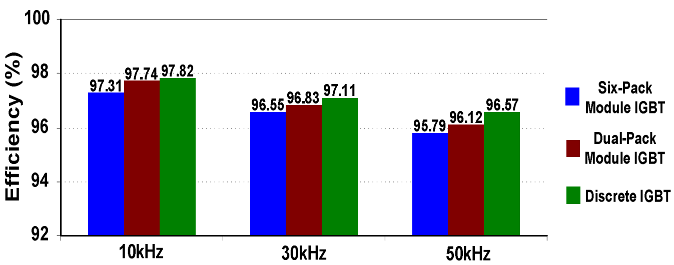

Fig. 4. The efficiency of the three-phase full-bridge inverter of the DWHR system for different switching frequencies, in case that either a six-pack module, or dual-pack modules, or discrete IGBT power devices are employed.

The total number of failures per 10^6 hours of the DWHR system for various switching frequencies is presented in Fig. 3, for the case that a common heat sink for all power devices is used. It is observed that by using a single six-pack module instead of three dual-pack modules, or six discrete power IGBT devices, the resulting total number of failures per 10^6 hours is lower by 2.63-3.34% and 5.84 8.21%, respectively. Thus, the six-pack module provides higher reliability to the overall DWHR system. Also, increasing the switching frequency of the three-phase full-bridge inverter results in an increase of the inverter total failure rate. Thus, in terms of reliability, it is preferable to operate the three-phase full-bridge inverter with a low switching frequency, but without violating the requirements imposed by the specifications of the DWHR system.

The power conversion efficiency of the DWHR system for various switching frequencies, in case that the power semiconductors are mounted on a common heat sink, is depicted in Fig. 4. It is observed that increasing the switching frequency results in a reduction of efficiency. However, using a lower switching frequency results in a degradation of the inverter power quality. In more details, Fig. 5 presents the efficiency and the Total Harmonic Distortion, THD_i, of the current at the PM generator side, for the case of a three-phase full bridge inverter (with a suitable three phase LCL filter at the PM generator side). According to those results, the efficiency drops almost linearly as frequency rises – due to the fact that the switching losses are increasing while the conduction losses remain almost constant. On the other hand, THD_i increases by 1% roughly as switching frequency decreases from 50 kHz down to 10 kHz. Nevertheless, THD_i is generally low (lower than 3.5%) and so it is not expected to raise compatibility issues with the relevant power quality standards, such us the MIL-STD-704F [21]. These outcomes highlight the fact that the selection of lower switching frequency is valid – due to the SPWM modulation that reduces significantly the THD_i value – unless the power density of the inverter is lower than the qualifications of the DWHR system (higher volumes of passive filters).

Moreover, the inverter efficiency when six discrete IGBT devices are used is higher by 0.08-0.48% and 0.52-0.81%, than the efficiency obtained in case that three dual-pack modules or one six-pack module, respectively, are employed [22].

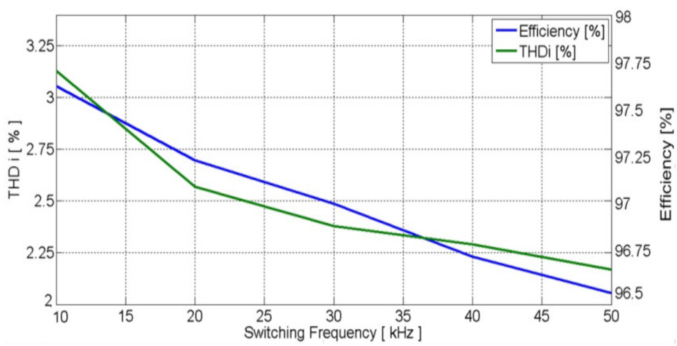

Fig. 5. THD_i and Efficiency parameters of the three-phase full-bridge inverter of the DWHR system for different switching frequencies, in case that discrete IGBT power devices are used to build the power inverter.

The number of failures per 10^9 hours of the individual components comprising the three-phase full-bridge inverter of the DWHR system, in case that the switching frequency is equal to 50 kHz and the power devices are mounted on a common heat sink, are illustrated in Fig. 6. It is observed that the highest failure rate is exhibited by the DC-bus capacitor, while the filter inductor features the lowest failure rate among all devices of the power inverter.

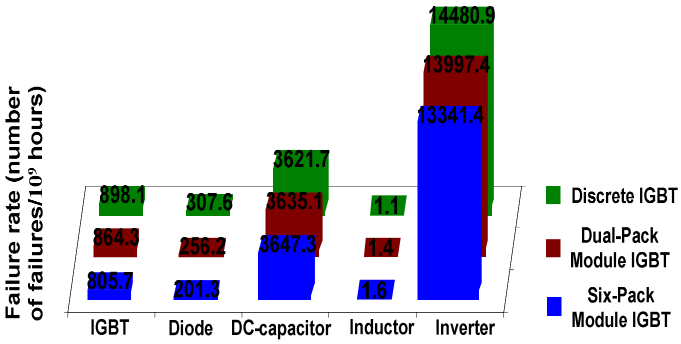

Fig. 6. The failure rate of the individual devices comprising the three-phase full-bridge inverter of the DWHR system for a 50 kHz switching frequency, in case that either a six-pack module, or dual-pack modules, or discrete IGBT devices are used.

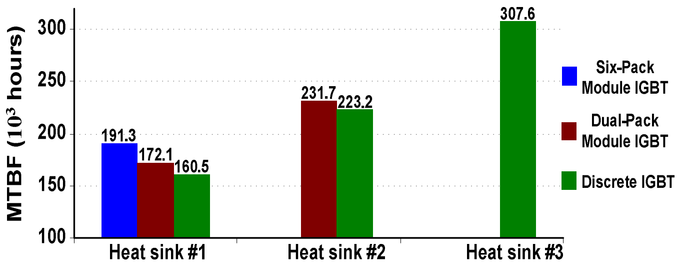

Fig. 7. The MTBF of the three-phase full-bridge inverter of the DWHR system for a 30 kHz switching frequency, in case that either a six-pack module, or dual-pack modules, or discrete IGBT power devices are used to build the power inverter.

The MTBF (in 10^3 hours) of the three-phase full-bridge inverter of the DWHR system for a 30 kHz switching frequency and various heat sink types, in case that either a six pack module, or dual-pack modules, or discrete IGBT power devices are used to build the power inverter, are depicted in Fig. 7. The thermal resistance, θ_{ca}, of heat sinks #1, 2 and 3 is equal to 0.28, 0.19 and 0.10 $^oC/W$, respectively. The heat sink type #1 has been used in all power device configurations (i.e. six-pack module, dual pack modules and discrete IGBTs), the heat sink type #2 has been applied in the dual-pack modules and discrete IGBT cases, while heat sink #3 has been employed only for the discrete IGBTs structure. According to Fig. 7, the selection of the heat sink type affects the reliability of the power inverter. In case that heat sink type #1 is used, then the MTBF of the inverter which is built using a six-pack module is higher by 10.04% and 16.10%, respectively, than the MTBF resulting when three dual-pack and discrete IGBT devices are employed for constructing the power inverter. Using three dual-pack modules on the heat sink type #2 results in an MTBF which is higher by 3.67% than the MTBF of the power inverter comprising discrete IGBT power devices (also mounted on the heat sink type #2). Finally, using heat sink #3 results in an MTBF of the power inverter which is higher by 47.82% and 27.44%, respectively, than the MTBF of the power inverter which is built using heat sinks type #1 and #2.

V. Conclusion

Dynamic waste heat recovery (DWHR) systems are incorporated in All-Electric Aircrafts for converting the kinetic energy of exhaust gas into electric energy. Because of their design simplicity, the three phase full-bridge inverters comprise a major subsystem of such a configuration. DWHR systems must exhibit a high reliability, in order to comply with the safety requirements of aircraft systems.

Till present the reliability features of the power conversion structures employed in aircraft DWHR systems had not been explored. In this paper, the performance of the three-phase full-bridge inverter of a DWHR system in terms of reliability has been investigated. The design results demonstrated that the reliability of the DWHR system is affected by the selection of design parameters, such as the switching frequency of the power inverter and the type of the heat sink where the power devices are mounted on. Also, the configuration of the power devices in a single six-pack module, or three dual-pack modules, or six discrete IGBT devices has a significant impact on the overall reliability of the three-phase full-bridge inverter. According to the design results, the highest reliability (i.e. lowest number of failures per 10^6 hours) of the DWHR system is obtained when applying a low switching frequency modulation in combination with a single six-pack module.

The reliability analysis method, which has been presented in this paper, comprises a valuable tool for optimizing the design of the power electronic interfaces employed in DWHR systems, such that the reliability is maximized.

Future work includes the application of the proposed technique in additional inverter topologies, which are suited for DWHR systems as well, in order to perform a comparative reliability study.

References

[1] K. Emadi, and M. Ehsani, "Aircraft power systems: Technology, state of the art, and future trends," *IEEE Aerospace and Electronic Systems Magazine*, vol. 15, no.1, pp. 28-32, January 2000.

[2] R. Burgos, G. Chen, F. Wang, D. Boroyevich, W. G. Odendaal, and J. D. Wyk, "Reliability-Oriented Design of Three-Phase Power Converters for Aircraft Applications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no.2, pp. 1249-1263, April 2012.

[3] J. Salmon, "Reliable 3-phase PWM boost rectifiers employing a stacked dual boost converter topology." *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 542-551, May 1996.

[4] A. Garcia, et al. "Reliable electro-mechanical actuators in aircraft." *IEEE Aerospace and Electronic Systems Magazine*, vol. 23, no. 8, pp. 19-25, August. 2008.

[5] G. C. Christidis, I.C. Karatzaferis, M. Sautreuil, E.C. Tatakis, and N.P. Papanikolaou, "Modeling and analysis of an innovative waste heat recovery system for helicopters", *15th European Conference on Power Electronics and Applications*, pp. 1-10, September 2013.

[6] G.C. Christidis, I.C. Karatzaferis, I.I Perpinias, M. Sautreuil, G. Bezes, N.P. Papanikolaou, M.Loupis, I.Spanoudakis, and E.C. Tatakis, "Innovative waste heat recovery systems in rotorcrafts," *Electrical*

Systems for Aircraft, Railway and Ship Propulsion, pp. 1-4, October 2012.

[7] Q. Chongming, and K.M. Smedley, "A general three-phase PFC controller for rectifiers with a parallel connected dual boost topology," *IEEE Transactions on Power Electronics*, vol. 17, no. 6, pp. 925-934, November 1983.

[8] J.C. Salmon, "Reliable 3-phase pwm boost rectifiers employing a stacked dual boost converter subtopology," *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 542-551, May 1996.

[9] M. Hartmann, J. Miniboeck, H. Ertl, and J.W. Kolar, "A Three-Phase Delta Switch Rectifier for Use in Modern Aircraft," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 9, pp. 3635-3647, September 2012.

[10] D. Bortis, S. Waffler, J. Biela, and J.W. Kolar, "25kW 3-phase unity power factor buck boost rectifier with wide input and output range for pulse load applications," *IEEE 16th Pulsed Power Conference*, pp. 1505-1508, June 2007.

[11] J. Sun, M. Chen, and K.J. Karimi, "Aircraft Power System Harmonics Involving Single-Phase PFC Converters," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 44, no.1, pp. 217-226, January 2008.

[12] G. Superti-Furga, and G. Todeschini, "Discussion on instantaneous p-q strategies for control of active filters," *IEEE Transactions on Power Electronics*, vol. 23, no. 4, pp. 1945-1955, July 2008.

[13] Y. Nishida, T. Kondoh, M. Ishikawa, and K. Yasui, "Three-phase pwm current-source type pfc rectifier (theory and practical evaluation of 12kW real product)," *Proceedings of the Power Conversion Conference*, pp. 1217-1222, April 2002.

[14] J. Karatzaferis, N. Papanikolaou, E. Tatakis, M. Loupis, and J. Spanoudakis, "Comparison and Evaluation of Power Factor Correction Topologies for Industrial Applications", *Journal of Energy and Power Enegineering*, vol. 5, pp. 401-410, August 2013.

[15] U. S. Department of Defense, "Reliability Prediction of Electronic Equipment," Department of Defense, Washington, DC, *Military Handbook MIL-HDBK-217F,* December 1991.

[16] S. Harb, and R.S. Balog, "Reliability of Candidate Photovoltaic Module-Integrated-Inverter Topologies," in *Proceedings of the 27th Annual IEEE Applied Power Electronics Conference and Exposition*, pp. 898-903, 5-9 Feb. 2012.

[17] E. Feilat, S. Grzybowski, and P. Knight, "Multiple stress aging of magnet wire by high frequency voltage pulses and high temperatures," in *Proceedings of the IEEE International Symposium on Electrical Insulation*, pp. 157-160, April 2000.

[18] E. Koutroulis, and F. Blaabjerg, "Design optimization of transformer-less grid-connected PV inverters including reliability," *IEEE Transactions on Power Electronics*, vol. 28, no. 1, pp. 325-335, January.2013.

[19] S. Saridakis, E. Koutroulis, and F. Blaabjerg, "Optimal design of modern transformerless PV inverter topologies", *IEEE Transactions on Energy Conversion*, vol. 28, no. 2, pp. 394-404, June 2013.

[20] F. Blaabjerg, U. Jaeger, and S. Munk-Nielsen, "Power losses in PWM-VSI inverter using NPT or PT IGBT devices," *IEEE Transactions on Power Electronics*, vol. 10, no. 3, pp. 358–367, May 1995.

[21] U. S. Department of Defense, "Aircraft Electric Power Characteristics," Department of Defense, Washington, DC, *MIL-STD-704F*, March 2004.

[22] S. Bifaretti, P. Zanchetta, and E. Lavopa, "Comparison of Two Three-Phase PLL Systems for More Electric Aircraft Converters," *IEEE Transactions on Power Electronics*, vol. 29, no. 12, pp. 6810–6820, December 2014.