Reliability Analysis of aircraft starter generator drive converter

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Abstract—Under the more electric aircraft (MEA) theme, many aircraft systems are being electrified. In a previous research work, an electric starter generator system for aircrafts was implemented. This paper presents the reliability of the drive converter—a 3 level neutral point clamped converter (3L-NPC) under an expected mission profile of a short haul aircraft. Wear-out failure based reliability of semiconductors and capacitors are considered along with reliability of gate drivers to estimate the overall reliability of the converter.

Index Terms—More electric aircraft (MEA), Power Electronics, Reliability, 3L-NPC

I. INTRODUCTION

Aviation industry is exploring means to cap emissions level at 2020 level and achieve net reduction of 50% in emissions by 2050. To achieve these goals, electrification of aircraft systems is being pursued [1]. Such electrified systems would include power electronic converters and their reliability must meet aerospace safety requirements. Prior works have estimated the reliability of power converters in various applications - railway traction converters [2], electric vehicle traction [3], wind power converters [4], PV inverters [5].

In this work, the system under study is an electric starter generator system designed under the Aircraft Electrical Starter-Generation System with Active Rectification Technology (AEGART) project [6]. A 3L-NPC converter is interfacing the electric motor/generator to the DC power grid.

The main research problem addressed in this work is estimation of reliability of power converters under aerospace operating conditions. Simulations are carried out considering the torque speed profile, DC link voltage and other parameters applicable to the AEGART system. Wear out failure mechanism of power converters are usually studied in detail. But random failures are also to be considered for applications in safety critical and high reliability applications. In a prior work on cosmic ray induced random failures [7], the effect of random failures and early failures are shown in relation to the overall system reliability. The importance of considering random failures are shown as it may have higher influence on the system reliability. Gate driver failure due to random failures are considered in this work to bring out the effect of random failures on the reliability of the converter.

II. AEGART SYSTEM DESCRIPTION

The operation of the starter generator system is briefly described. At startup the AEGART system acts as a starter to the main turbine. Hence the drive converter functioning as inverter is supplying power at maximum torque to spin-up the main turbine upto start-up speed. Once the startup speed is achieved AEGART system stops powering the motor. The main turbine continues to speed up and the AEGART system starts generating power and supplies power to the DC grid once minimum generation speed is reached. During the entire flight phase after startup, the AEGART system continues to operate at rated operating speed and provides power to the electrical network. The torque speed profile of the system is shown in Fig. 1.

Fig. 1. Torque Speed profile of AEGART system

The torque speed details are summarized in Table I.

| Start-up Torque | 17.9 Nm |
|-----------------|---------|
| \( \omega_{\text{base}} \) | 8000 rpm |
| \( \omega_{\text{start}} \) | 12000 rpm |
| \( \omega_{\text{genmin}} \) | 19200 rpm |
| \( \omega_{\text{genop}} \) | 24000 rpm |
| \( \omega_{\text{genmax}} \) | 32000 rpm |

It is assumed that the system achieves base speed in 40 seconds and the same rate of motor speed change is assumed in the rest of the operation. A time delay of 30 seconds is considered from main turbine start to turbine achieving minimum generator speed. Based on the torque-speed profile as well as the flight phase a mission profile is generated for reliability calculations. The schematic of the 3L-NPC
The design parameters of the 3L-NPC converter are summarized in Table II.

![Fig. 2. 3L-NPC Bidirectional Rectifier](image)

### TABLE II

| 3L-NPC PARAMETERS |
|-------------------|
| \( V_{dc} \) | 270 |
| SW frequency | 16 kHz |
| Rated Power | 45 kW |

The rest of the paper reports detailed reliability calculations of the 3L-NPC converter. Mission profile for reliability calculations is derived based on the output power of the converter and ambient temperature. Loss estimation and thermal simulation is carried out to estimate the junction temperature of IGBTs and hot spot temperature of the capacitors. The simulated stress values (temperature and voltage) due to the expected mission profile is applied in Physics of Failure (PoF) models of lifetime estimation for IGBTs and DC link capacitors. For reference, a block diagram of lifetime estimation of IGBTs is shown in Fig. 3. Capacitor wear out based lifetime estimation follows similar steps. A simulation study on various failure rates for gate drivers is included to bring out the effect of random failures. Finally, Reliability Block Diagram (RBD) method is applied to derive system reliability for the converter from individual component reliability profiles.

### III. MISSION PROFILE OF AEGART SYSTEM IN A SHORT HAUL AIRCRAFT

Airlines aim to maximize flight time of aircrafts, typically of short haul flights. A typical short haul flight is around 1 hour flying time. The cruising altitude is assumed to be 30000 feet. Accounting for flight preparation, taxi, take-off, landing etc. a typical flight requires roughly 2 hours time from gate to gate. Assuming only day time operations, 6 flights per day are assumed. Summary of flight stages are shown in Fig. 4.

The duration of different flight phases assumed in this study is provided in Table III.

The following assumptions are made on the temperature gradient of the atmosphere. In the lower atmosphere up to 5000m a gradient of -6.5 degC/km is assumed. The cruising altitude temperature is assumed to be -50 degC at 10 km. Three different average ground level ambient temperature is assumed – 5, 15, 20 degC. Hence simulations are carried out 3 times to estimate losses and consequent thermal stresses in devices during operation in a year. Climb rates assumed in building the ambient temperature profile in summarized in Table IV.

The ambient temperature profile for one simulation run along with altitude variation is shown in Fig. 5. The ambient temperature profile based on the flight data along with the torque speed requirements of the AEGART system, as de-
scribed in [6], is applied to generate mission profile - Power and Ambient temperature of the 3L-NPC converter.

The main lifetime limiting factor of power electronic components is temperature stress. Thermal simulation is carried out to estimate temperature stress imposed on semiconductors and capacitors. Thermal simulation is carried out using Foster thermal impedance networks. It is graphically represented in Fig. 6 for IGBTs.

The IGBT module used in AEGART 3L-NPC is the module - F3L400R07ME4_B22 from Infineon. The module contains IGBTs with free wheeling diodes as well the neutral point clamp diode. The datasheet values for switching losses and on-state voltage drop is used to estimate the losses in the IGBTs. The modulation of IGBTs in 3L NPC follows the output voltage requirement and to ensure no unsafe operating modes. The modulation details are described in the Semikron application note [8]. The simulated junction temperature of IGBTs are used in reliability calculations.

The main source of loss in capacitors can be modelled using the equivalent series resistor (ESR) of the capacitor. Hence the rms current through the capacitor would yield the loss figure that can be fed into the thermal network to yield the capacitor hot spot temperature.

Based on the voltage rating of 270V and potential for higher voltage operation, B32778G4107K000 from TDK Epcos (100 uF, 400V) is considered for reliability analysis. A bank of 4 pairs of capacitors make up the DC link. Along with capacitance, the temperature rise in capacitor is also a design input for number of capacitor selection as per TDK Epcos

![Altitude and Temperature variation during Flight](image)

**Fig. 5. Altitude and Temperature variation during Flight**

**IV. POWER LOSS ESTIMATION AND THERMAL MODELLING OF 3L NPC CONVERTER**

The main lifetime limiting factor of power electronic components is temperature stress. Thermal simulation is carried out to estimate temperature stress imposed on semiconductors and capacitors. Thermal simulation is carried out using Foster thermal impedance networks. It is graphically represented in Fig. 6 for IGBTs.

**A. Junction temperature estimation of IGBTs**

The IGBT module used in AEGART 3L-NPC is the module - F3L400R07ME4_B22 from Infineon. The module contains the semiconductors in the red highlighted portion of Fig. 2 - 2 IGBTs with free wheeling diodes as well the neutral point clamp diode. The datasheet values for switching losses and on-state voltage drop is used to estimate the losses in the IGBTs.

\[
P_{SW_{-IGBT}} = fsw((E_{on} + E_{off}) \cdot (\frac{I}{I_{ref}})^{K_i} \cdot (\frac{V_{off}}{V_{ref}})^{K_v}) \quad (1)
\]

**P_{cond} = Vce_{on} \cdot I \quad (2)**

Ki is assumed to be 1 and Kv is taken as 1.3 in (1). Junction temperature can be obtained as shown in Fig. 6 by applying the power losses to the Foster network.

\[
T_{j(IGBT)}(t) = P_{\text{loss tot}_{-IGBT}}(t) \cdot Z_{th_{-IGBT}(j-c)}(t) + T_c(t) \quad (3)
\]

\[
T_c(t) = \left( \sum P_{\text{loss}_{IGBT}}(t) + \sum P_{\text{loss}_{Diodex}}(t) \right) \cdot [Z_{th_{(c-h)}}(t) + Z_{th_{(h-a)}}(t)] + T_a(t) \quad (4)
\]

Tj, Tc and Ta are junction temperature, case temperature and ambient temperature respectively. As can be seen in (4), the junction temperature is dependent on losses from other semiconductors in the same module. In the case of Infineon module, the outer and inner IGBT experiences different losses. The modulation of IGBTs in 3L NPC follows the output voltage requirement and to ensure no unsafe operating modes. The modulation details are described in the Semikron application note [8]. The simulated junction temperature of IGBTs are used in reliability calculations.

**B. Hot spot temperature estimation of Capacitors**

The main source of loss in capacitors can be modelled using the equivalent series resistor (ESR) of the capacitor. Hence the rms current through the capacitor would yield the loss figure that can be fed into the thermal network to yield the capacitor hot spot temperature.

**Fig. 6. Thermal Simulation using Foster Network**

**Fig. 7. Capacitor hot spot estimation**

An equation to derive rms current through DC link capacitors for a 3L-NPC converter is derived in [9].

\[
I_{Crms}^2 = \frac{3 I_m^2 M}{4\pi} \left(\sqrt{3} + \frac{2}{\sqrt{3}} \cos(2\phi)\right) - \frac{9}{16} \left(\frac{I_m M}{2}\right)^2 \cos^2(\phi) \quad (5)
\]

Based on the voltage rating of 270V and potential for higher voltage operation, B32778G4107K000 from TDK Epcos (100 uF, 400V) is considered for reliability analysis. A bank of 4 pairs of capacitors make up the DC link. Along with capacitance, the temperature rise in capacitor is also a design input for number of capacitor selection as per TDK Epcos...
application note. Hence the number of capacitors is chosen such that the capacitor temperature rise is limited to datasheet specification. Using (5) and the datasheet value for thermal impedance, the capacitor hotspot temperature is calculated during the flight.

V. RELIABILITY OF INVERTER SYSTEM

Based on temperature values and DC link voltage from previous section, the following components are separately treated to estimate reliability of the converter system – Outer IGBT switch, Inner IGBT switch and DC link capacitor.

A. Lifetime model and Reliability estimation of IGBTs

The well-known extended Coffin-Manson model with Arrhenius term is chosen as the lifetime model in this study. The process of extracting lifetime data using junction temperature and lifetime models is described in [10]. Rainflow algorithm is used to extract thermal cycles to be applied in the lifetime model. Thermal cycling causes mechanical stresses in the semiconductor module. Miners rule of linear damage accumulation is used to calculate the lifetime of the module based on thermal cycles experienced by the power module. As per miners rule, once the accumulated damage equals 1, the useful lifetime of a device is consumed.

\[
N_f = A \cdot dT^\alpha \cdot e^{E_a/k_B \cdot \frac{1}{T}}
\]  

\[
A = 3.025 \times 10^5; \alpha = -5.04; E_a = 9.891 \times 10^{-20}
\]

Application of the miner’s rule on damage accumulation caused by thermal cycles gives a lifetime of 2027 years for outer IGBT (S1) and 451 years for the inner IGBT (S2) based on the mission profile considered. The inverter is operating in generating mode during most of the flight and hence the lifetime predictions are not surprising. The outer IGBTs hardly experience any losses during generation mode at high power factor while the inner IGBTs would be conducting current during both generation and motoring mode. As with any lifetime model, statistical variations need to be considered to get reliability figures from lifetime data. Hence the following process as described in [11] is followed to perform a Monte-Carlo simulation assuming a 5% variation in device parameters. Weibull distribution is used to fit lifetime distribution data of failure modes caused by repetitive mechanical stress. As thermal stresses leads to repetitive mechanical stress, Weibull distribution is used to fit lifetime distribution from Monte-Carlo simulation.

The reliability figures thus obtained for the IGBTs and the \( \beta \) and \( \eta \) factors of the Weibull distribution are shown in Fig. 8. The loss figures and predicted lifetime values are highly dependent on the switching losses and conduction losses of the devices as well as the expected mission profile of the converter.

B. Lifetime model and Reliability estimation of Capacitors

The major factors affecting the lifetime of film capacitors are temperature, voltage stress and humidity [12]. A lifetime model considering the effect of all three parameters are provided in [13]. In this work the effect of humidity is not considered.

\[
L = L_0 \cdot e^{\left(\frac{-U}{U_0}\right)} \cdot e^{\beta \left(\frac{U - U_0}{U_0}\right)}
\]  

\[
L_0 = 20000 \text{hours}; T_0 = 25 \text{C}; \beta = 3.5; U_0 = 400 \text{V}
\]

As with IGBTs, application of the Miner’s rule of linear damage accumulation on the capacitor damage gives a lifetime of 254 years based on the mission profile considered. Statistical effects is to be considered for the capacitor as well. The method to derive reliability figure by considering uncertainties in capacitor lifetime model is described in [14]. The unreliability curve of capacitor lifetime model is shown in Fig. 9.

C. Lifetime model of Gate Drivers

The effect of the reliability of gate drivers is usually not included in many reliability estimations. For high reliability applications like aerospace, every component that can cause a failure needs to be considered while estimating system reliability. Failure mechanisms of gatedrivers would be a combination of semiconductor and capacitor failure modes. Gate driver lifetime models are not readily available in literature. Due to lack of sufficient prior work, gate driver reliability is modelled using a constant failure rate. There are 12 gate drivers in a 3L-NPC and the effect of gate driver reliability when considering the whole converter is shown considering three failure rates - 0.01 (1 failure every 100 years), 0.001 (1 failure every 1000 years) and 0.0001 (1 failure every 10000 years).

D. Reliability Block Diagram method for full converter reliability

RBD method is used to combine the reliability figures of individual components to generate the overall reliability of the inverter system. In RBD each component that is necessary for operation of the system is connected in series and the reliability curves are multiplied together. Redundancy as well as m out of n systems can also be handled by RBD method.
The reliability block diagram for the 3L NPC converter is shown in the Fig. 10. In the 3L-NPC case, the reliability of the 6 outer IGBTs, 6 inner IGBTs, 8 DC link capacitors as well as 12 Gate Drivers are combined to obtain the inverter system reliability.

Figure 11 shows the reliability of the whole converter when a gate driver failure rate of once every 100 years (1% per year) is modelled. It can be clearly seen that the reliability of the whole system is dominated by the reliability of gate drivers. Hence the importance of focussing attention on random failures along with wearout failures is clear. The importance of gate driver reliability is further clarified in Fig. 12 where different gate driver failure rates are modelled. As can be seen, to achieve a system reliability dominated by wearout failure modes, a failure rate of once every 10000 years per gate driver (0.01% per year) should be achieved by design.

VI. RESULTS AND DISCUSSION

In this work, the reliability calculations of a starter generator drive converter for MEA is presented. Reliability of IGBTs and capacitors are derived using PoF models. As expected, outer and inner IGBTs in the 3L-NPC converter has different reliabilities with the inner IGBT having a lower lifetime than the outer IGBT. The effect of gate driver reliability in the analysis highlights the importance of considering the whole system reliability in case of multi-level converters. Effect of random failures on system reliability is clearly shown in the reliability of the 3L-NPC converter. Random failure modes require more careful analysis and particular attention must be placed on them in case of high reliability and mission critical applications.
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