Serious Incident

Aircraft Type and Registration:	ATR 72-202, G-NPTF
No & Type of Engines:	2 Pratt & Whitney Canada PW121 turboprop engines
Year of Manufacture:	1990 (Serial no: 192)
Date & Time (UTC):	17 January 2023 at 0425 hrs
Location:	East Midlands Airport
Type of Flight:	Commercial Air Transport (Cargo)
Persons on Board:	Crew - 2 Passengers - None
Injuries:	Crew - None Passengers - N/A
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	37 years
Commander's Flying Experience:	5,264 hours (of which 583 were on type) Last 90 days - 74 hours Last 28 days - 28 hours
Information Source:	AAIB Field Investigation

Synopsis

During the latter stages of a CAT II automatic approach to East Midlands Airport, the aircraft suffered a significant electrical malfunction. This caused the loss of the co-pilot's flight instrument displays and triggered a number of warnings and cautions. The crew executed a go-around and diverted to Birmingham International Airport. A wiring defect, probably caused by incorrect use of mechanical wire stripping tools at a third-party organisation, was the cause of the electrical malfunction. Action has been proposed by the equipment manufacturer and has been taken by the third-party maintenance organisation to promote the use of alternative tooling to prevent a reoccurrence.

History of the flight

The crew reported for duty at 2320 hrs at East Midlands Airport (EMA). The aircraft's tech log contained an entry for an Acceptable Deferred Defect to the TCAS system but there were no other technical issues. The aircraft was de-iced due to frost conditions at EMA, and it departed at 0030 hrs. The flight to Belfast International (BFS) was without incident and the aircraft arrived at 0150 hrs. The crew conducted a routine turnaround and, due to low temperatures and active frost in BFS, the aircraft was again de-iced before its departure at 0310 hrs.

The departure from BFS and the cruise toward EMA were uneventful. Due to a forecast of freezing fog at EMA the crew prepared and briefed for a CAT II approach with the commander as PF. As they approached EMA, they were told to expect to hold due to delays caused by the Low Visibility Procedures in force at EMA. The aircraft entered the hold as directed and after approximately 10 minutes ATC gave radar vectors to intercept the ILS for Runway 27 at EMA.

The initial stages of the CAT II approach on the ILS proceeded normally. The aircraft achieved stable approach conditions at 1,300 ft amsl and, at 1,000 ft radio altitude, the crew saw the correct dual autopilot indications on the aircraft displays. At approximately 500 ft radio altitude the aircraft entered cloud. Shortly after that the ELEC caution on the Centralised Crew Alerting System (CCAS) illuminated. This indication directed the crew to check the electrical indications on the overhead panel where they noted that the DC GEN2 FAULT amber light was flashing. The co-pilot's Electronic Attitude and Direction Indicator (EADI) and Electronic Horizontal Situation Indicator (EHSI) were also flashing in time with the ELEC and DC GEN2 captions. The autopilot (AP) disconnect horn sounded and the flight director (FD) modes on the EADI disappeared, although the FD guidance bars remained visible and appeared to give sensible indications. The crew decided to go around.

As power was applied for the go-around there were numerous audio and visual warnings including Enhanced Ground Proximity Warning System (EGPWS) warnings for "TERRAIN AHEAD" and "TOO LOW GEAR". The co-pilot's EADI and EHSI continued to flash, and his ASI was cycling from maximum to minimum speed. The co-pilot made a positive rate of climb call and then, on the commander's order, retracted the landing gear. The commander's EADI and EHSI went blank for a few seconds but then recovered before blanking again for a few seconds approximately one minute later. The standby instruments continued to work normally.

During the climb, both pilots recalled hearing sounds that they believed were electrical relays cycling. The Autopilot Display Unit (ADU) was also flashing, and the crew were unable to reselect the AP. In the climb, the crew realised that the flap setting had remained at 30 and they retracted the flaps; flaps limiting speed was not exceeded. They carried out the published go-around procedure, levelled at 3,000 ft amsl and turned right toward the EME NDB (Figure 1).

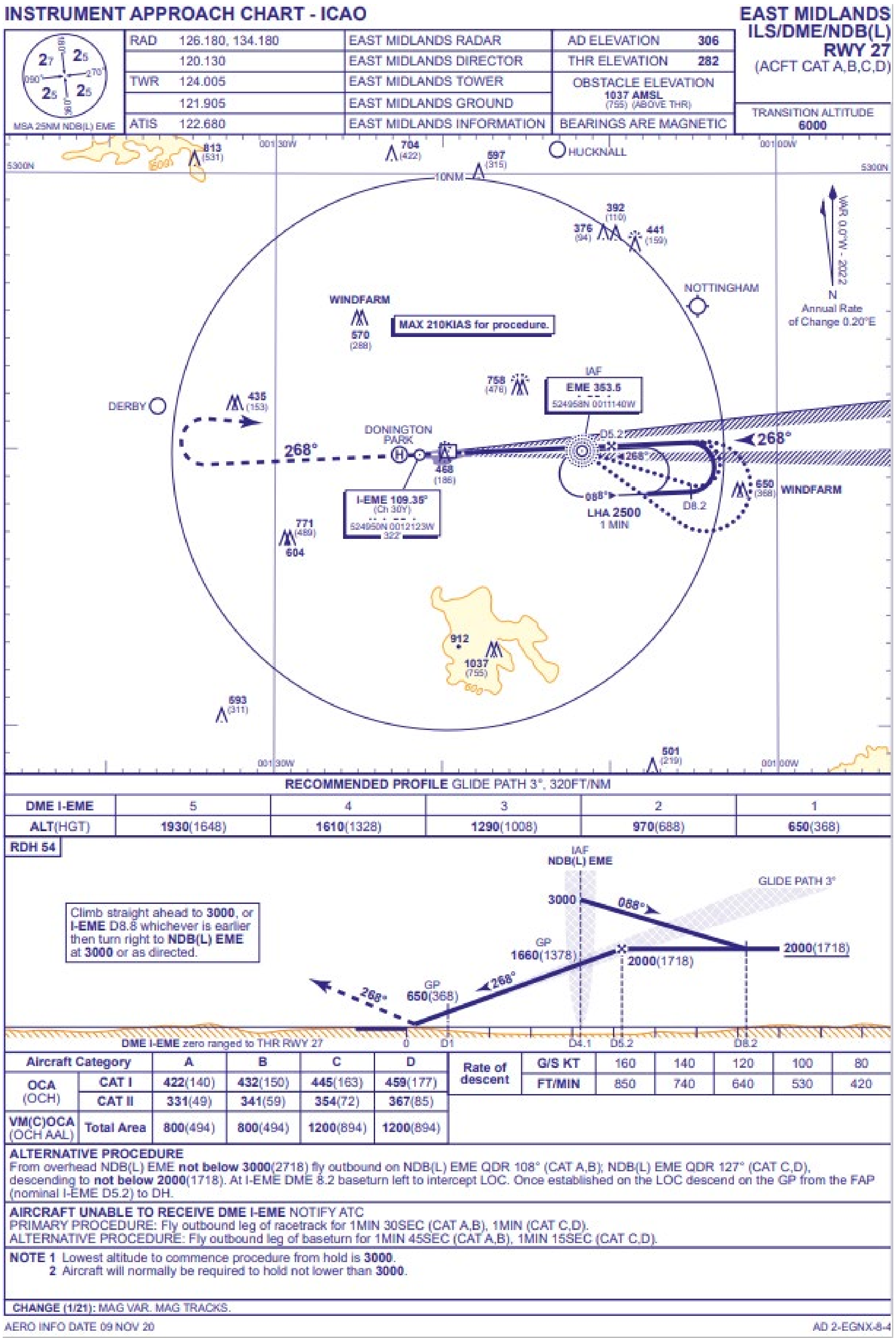

Figure 1

EMA approach and go-around procedure

Once level, the crew made a PAN call to ATC but heard no response. They then tried to contact ATC on the distress frequency 121.5 MHz but still received no response. They reselected the EMA Tower frequency, selected 7600 on the transponder, then broadcast a MAYDAY. Amidst audio conditions that the crew described as severe "static", the pilots heard a faint message from ATC to contact EMA Radar. They changed to the appropriate frequency and from that point communications were restored. The crew requested radar vectors for a diversion to Birmingham International Airport (BHX).

As the DC GEN2 FAULT amber light was flashing, the crew carried out QRH actions for a DC GEN2 fault, which involves selecting that generator to OFF. Approximately seven minutes elapsed from the start of the event until the crew deselected DC Gen 2. When the DC generator 2 was switched off the audio and visual warnings stopped, the co-pilot's screens stopped flashing and went blank, and a number of caution lights remained illuminated in the overhead panel. The commander recalled that the "Bus Tie Contactor (BTC) did not close" as would have been expected so the DC Bus 2 was unpowered. The crew consulted the QRH loss of equipment list for DC Bus 2 off (Figure 2).

Lost Equipment List

Air
- LANDING ELEVATION indicator

Auto flight
- ADU

Doors
- DOORS UNLK Lights
- CDLS

Fire Protection
- NAC OVHT

Flight controls
- STBY PITCH TRIM CTL
- F/O STICK SHAKER
- TLU AUTO CONTROL

Hydraulic Power
- GREEN PUMP
- HYD PWR AUX PUMP IND
- HYD PWR AUX PUMP AUTO MODE

Ice and Rain protection
- F/O STATIC PORTS ANTI ICING
- F/O SIDE WINDOWS ANTI ICING
- F/O WINDSHIELD HTG indicator
- F/O PROBES indicator
- F/O WIPER

Indicating - Recording Systems
- CAP AMBER ALERTS (except MAINT PNL, PRKG BRK, MFC)

Landing Gear
- SECONDARY indicator

Lights
- F/O CHARTHOLDER
- F/O READING Lights
- INTEGRATED INSTRUMENTS Lights
- INTEGRATED PANELS Lights
- TAXI & T.O Lights
- WING Lights
- PAX SIGNS Lights

Navigation
- F/O EADI/EHSI
- SGU #2
- VOR #2
- ILS #2
- DME #2
- ADF #2
- CAPT RMI
- VHF #2
- ATC #2
- ADC #2
- ALT ALERT #2
- F/O CLOCK
- TCAS or T2CAS (if installed)
- GPS KLN90 (if installed)

Power Plant
- FF/FU #2
- FUEL TEMP #2
- FUEL CLOG #2
- OIL PRESS #2
- OIL TEMP #2
- IDLE GATE CAUTION

Figure 2

DC Bus 2 Lost Equipment List

In addition to the items on the Lost Equipment list, the commander also stated that there remained additional electrical failures to those on the list such as the loss of the environmental control system recirculation fan and the Aircraft Performance Monitoring System.

The crew recognised that the main battery was discharging and the Green hydraulic system which lowers the landing gear was unpowered. The commander was concerned for further electrical failures should the aircraft remain airborne for longer than the published 30-minute life of the main battery. The crew did the performance calculations for landing at BHX and used the Blue hydraulic system to pressurise the Green hydraulics to allow the landing gear to be lowered.

The left navigation receiver could be tuned to the ILS for Runway 33 at BHX, but all automatic flight functions remained unavailable. The commander flew a manual raw data ILS approach to Runway 33 and the aircraft landed without further incident and taxied to stand. The aircraft was taken out of service for detailed troubleshooting on the cause of the electrical issues experienced by the crew.

Meteorology

The weather report for EMA at 0350 hrs gave the following conditions: wind 270° at 8 kt, visibility 400 m in freezing fog, cloud broken at 100 ft and the temperature and dewpoint both -2°C. This was as forecast, and the crew had prepared for such conditions.

The weather at BHX at 0350 hrs was wind 230° at 1 kt, CAVOK, temperature -5°C and dewpoint -6°C.

Recorded information

The aircraft's flight data recorder (FDR), cockpit voice recorder (CVR) and EGPWS were downloaded for analysis of the recorded information, together with ground radar data from Clee Hill and Claxby. Relevant information from the CVR recording is included in the history of the flight.

The recorded radar track data for the approach to EMA and diversion to BHX are shown in Figure 3. The radar returns for the approach to EMA included pressure altitude from the aircraft's Mode S transponder. However, from 0418:51 hrs, with the aircraft within a nautical mile of the runway at about 400 ft aal, the transponder transmissions stopped, and the aircraft continued to be tracked only by primary radar for the remainder of the flight.

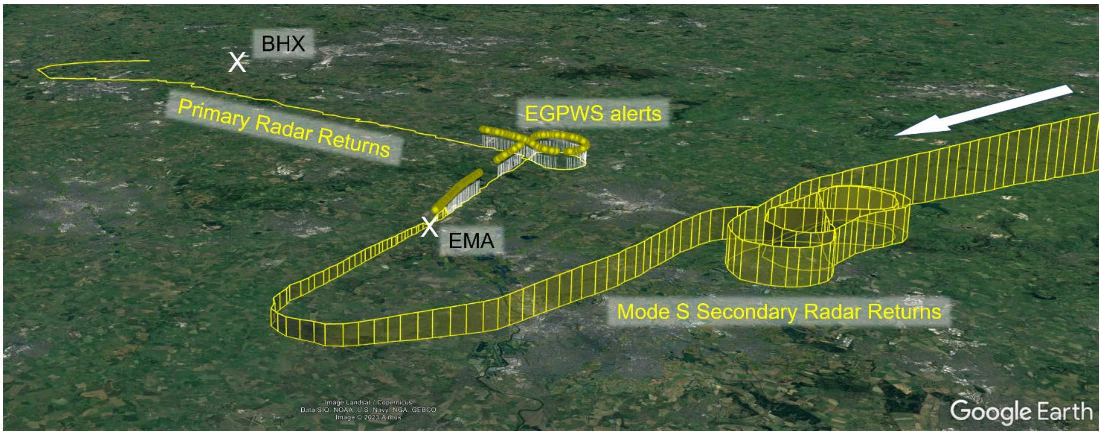

Figure 3

Radar ground track

Data from the aircraft's FDR show that just after 0418 hrs the master warning alert was triggered together with spurious VHF 2 transmission indications and radio altimeter heights (Figure 4). The spurious heights were intermittent over a period of seven minutes and ten seconds and were sufficiently low to trigger 31 EGPWS alerts (2x "PULL UP", 6x "TERRAIN, TERRAIN", 6x "TOO LOW TERRAIN", 12x "TOO LOW GEAR" and 5x "BANK ANGLE, BANK ANGLE") – see Figure 3 for the location of the aircraft during these EGPWS alerts. Note that some of the alerts coincided with others so not all were heard on the CVR.

The spurious VHF 2 transmission indications continued for the remainder of the flight as did the master warning alert.

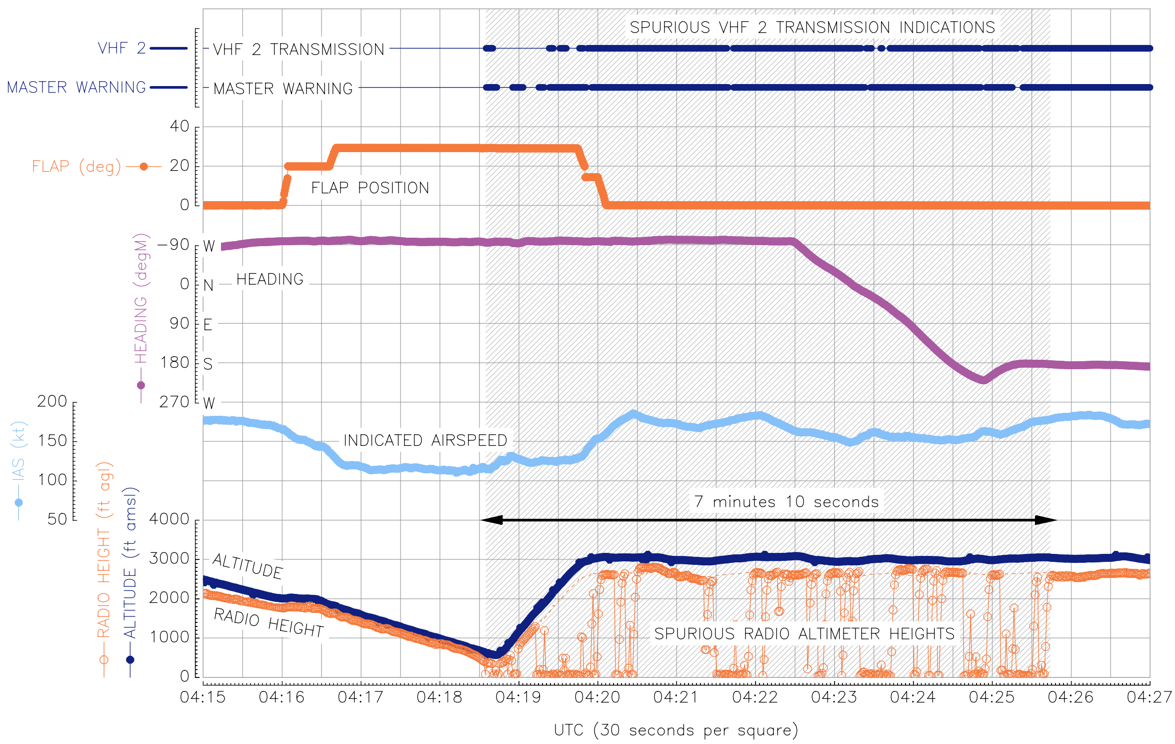

Figure 4
FDR data

Aircraft information

The ATR 72-202 is a twin turboprop regional aircraft. G-NPTF was manufactured in 1990, held a valid ARC and was being operated as a cargo variant. G-NPTF joined the operator's fleet in May 2022.

Category II (CAT II) operations

For a CAT II ILS approach, the aircraft's single autopilot is automatically coupled to both Horizontal Situation Indicators by 1,200 ft radio altitude and confirmed by the presence of dual CPL (couple) indications on the ADU. If the dual indications are not present by 1,000 ft radio altitude, then the approach may not be continued below 200 ft aal.

The minimum RVR for the aircraft to conduct a CAT II approach is as follows:

- Touchdown 300 m
- Mid-Point 125 m
- Stop-End 75 m

The operator's operations manual Part B states '*Any failure that is not completely 'treated' (ATR terminology) before 1000 ft AAL, or that occurs below 1000 ft AAL, shall lead to a go around.*'

Maintenance history

Routine scheduled maintenance had been completed on G-NPTF two days before the accident flight. During the check, the No 2 engine DC starter-generator (DC Gen 2) brushes were found worn to their service limit, so it was replaced with an overhauled unit. The replacement starter-generator had been overhauled and bench tested in accordance with the manufacturer's Component Maintenance Manual (CMM) six months previously and was supplied with a valid EASA Form 1 Authorised Release Certificate.

Electrical systems

During flight, the ATR 72-202's electrical power is provided by the following sources:

- Two engine-driven 28V DC starter-generators, one on each engine (DC Gen 1, DC Gen 2).
- Two DC-supplied static inverters, providing constant frequency 26V and 115V AC power.
- Main and Emergency 24V DC batteries.
- Two propeller-driven AC frequency wild generators providing 115V AC.

Two separate electrical networks, No 1 (left side) and No 2 (right side) for both DC and constant frequency AC power operate independently. In case of failure of one network, each side of the DC or AC network can be connected to its respective DC or AC opposite side, using the DC BTC or the AC Bus Tie Relay (BTR).

The 115V AC wild network is standalone from the DC and constant frequency AC networks.

Each electrical network powers a series of buses, which in turn distribute power to equipment and services that are shared amongst the networks to provide system redundancy.

The DC network is shown in Figure 5.

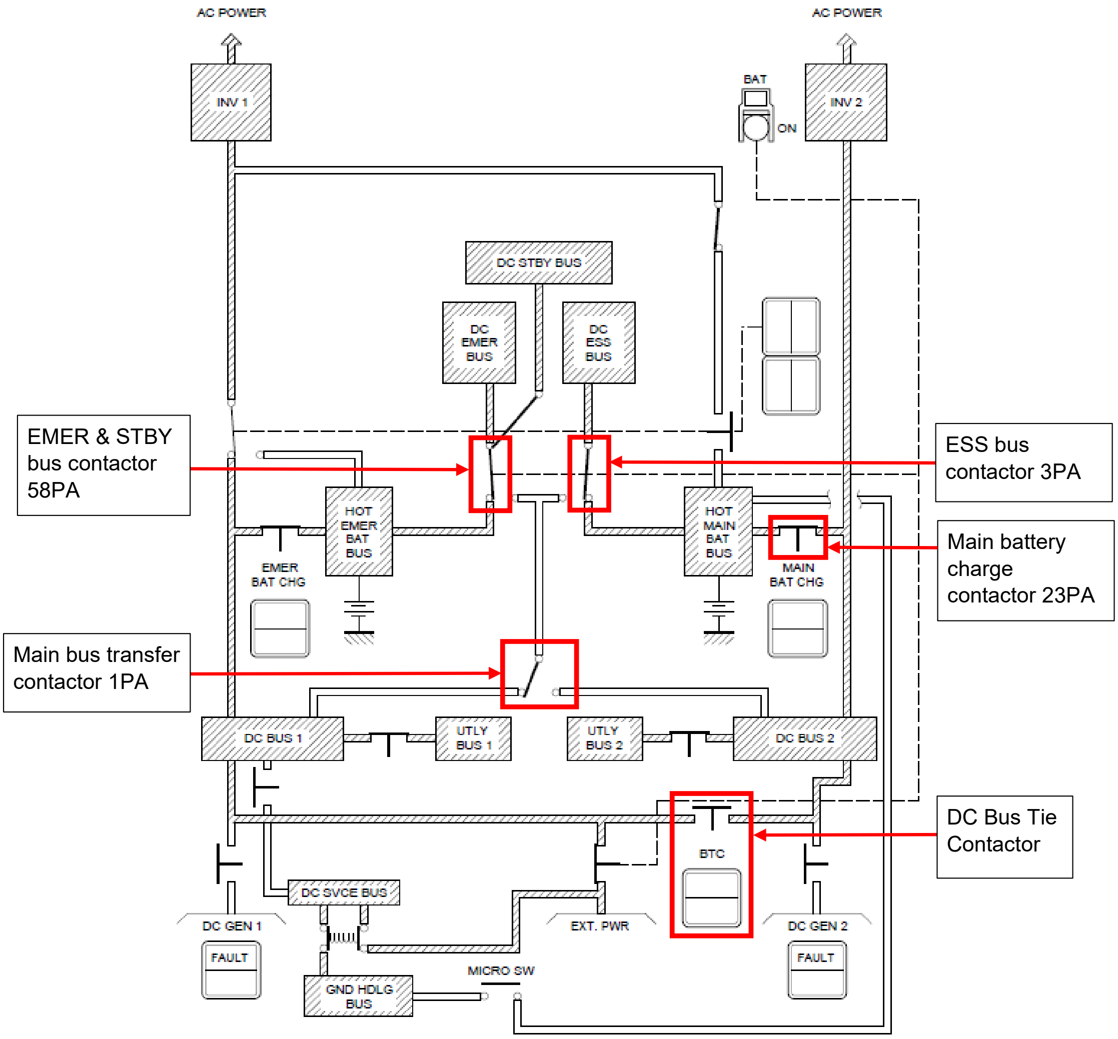

Figure 5

DC network schematic

The DC 1 and DC 2 networks supply power to corresponding static inverters, each providing constant frequency AC output on AC 1 and AC 2 networks (Figure 6). Each inverter has a 26 V and a 115 V 400 Hz output.

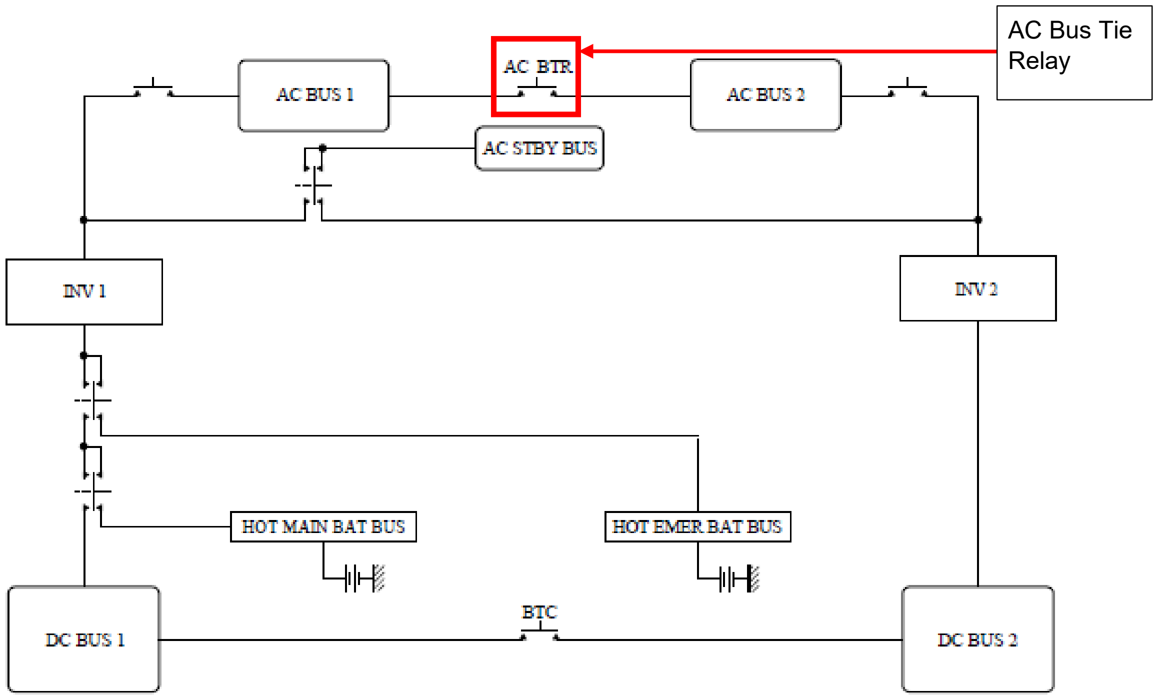

Figure 6

Constant frequency AC network

Emergency network power distribution

Cross supply and redundancy between the buses is provided by a series of contactors and switches including, among others, the BTC, BTR and main bus transfer contactor 1PA. Their operating logic is managed by Bus Power Control Units (BPCU) and Multi-Function Computers (MFC) to provide automatic reconfiguration in case of one DC Generator loss.

If one of the DC generators fails, its dedicated GCU isolates the affected DC network and the BPCU closes the BTC so that the other DC generator can provide power to both DC main buses. The BTC can also be isolated (ISOL) via a pushbutton switch on the flight deck overhead panel, preventing the main DC 1 and DC 2 buses being linked. The 1PA contactor further allows DC Bus 1 or DC Bus 2 to power the ESS, STBY and EMER Buses, if either or both of the 3PA and 58PA contactors are unable to be controlled by the MFCs.

Constant frequency AC 1 and AC 2 are linked by the BTR that operates in a similar manner to connect both AC networks together in case of a single inverter failure. If the BTC is automatically closed by the BPCU, the BTR will be closed by MFC 1 after a 10 second delay. If the BTC pushbutton switch is manually set to ISOL, the BTR is also isolated, preventing AC 1 and AC 2 from being linked.

If both DC generators fail, critical flight systems and equipment on the DC Emergency (EMER), Standby (STBY) and Essential (ESS) buses are powered by the main and emergency batteries. On G-NPTF, this gives up to 30 minutes of flight time to land the aircraft.

DC starter-generator

There are two DC starter-generators fitted to the aircraft, one to each engine. The generators are numbered by which engine they are fitted to: DC Gen 1 and DC Gen 2. Each generator separately supplies DC Bus 1 and DC Bus 2.

The starter-generator operates in two modes. Firstly, as a starter during the engine start sequence, when it uses an external power source[1] to rotate the engine up to its self-sustaining speed of 45% NH[2]. At this point, the unit stops providing starting torque. When NH then reaches 61.5%, the unit begins to operate as a DC generator, providing power to its respective DC Bus network.

NH is measured by a magnetic speed sensor within the starter-generator. The speed sensor assembly consists of a conical metal speed disc with equally spaced holes around its face, that is attached to the unit's rotating shaft, and a magnetic sensing unit positioned above the disc (Figure 7). As the disc rotates, the holes pass the sensor. The change in air gap detected as the holes pass creates an output voltage from the magnetic sensor which is translated into the NH measurement.

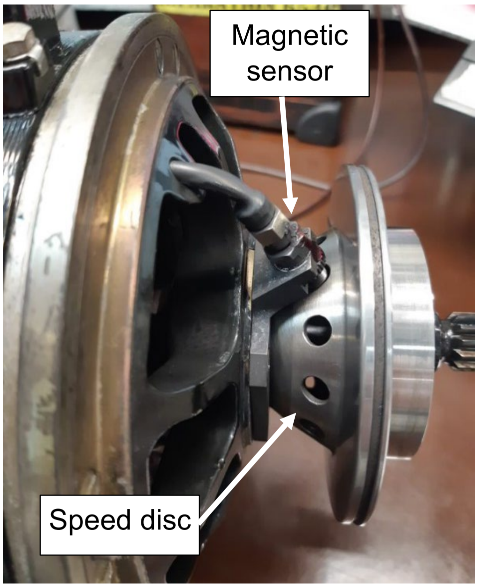

Figure 7
Speed sensor assembly

Electrical system protection

GCUs monitor the supply from the DC generators. If a fault is detected, the GCU will open the generator contactor between the generator and its main DC Bus to isolate it. A DC GEN FAULT pushbutton caption will subsequently illuminate on the overhead panel and an ELEC caution will appear on the CCAS.

Footnote

1 Either ground power, aircraft main battery, or a combination of main battery and opposite starter-generator (cross-start).

2 NH High pressure compressor rotational speed, displayed as a percentage of maximum rotational speed.

The GCUs also monitor the generator speed sensor output signal for fault detection at the 45% and 61.5% NH points. If the speed sensor signal is not detected correctly, the GCU will trigger the sequence of events to isolate the respective DC Bus and send a signal to the BPCU to close the BTC. The BTR will then close 10 seconds later.

If the BTC is cycled three or more times within two seconds, an inbuilt system protection locks it open so it will not tie. When the cause of the lock-out is no longer present, the BTC can be reset by cycling the BTC pushbutton switch located on the flight deck overhead DC electrical panel. The conditions that trigger a BTC lock-out are not detailed in the Flight Crew Operating Manual (FCOM). However, the system reset is described in the FCOM and the QRH. The BTR does not have such a system protection lock.

VHF communications

Two VHF systems (VHF 1 and VHF 2) are connected to a Remote Control Audio Unit (RCAU) which is powered by the DC ESS Bus. The RCAU centralises audio signals and enables the flight crew to communicate between themselves, make public address announcements (for passenger operations), or communicate to ATC. VHF transmission and reception mode connections are made via two internal relays.

The RCAU installed on G-NPTF has an emergency mode in the event of power supply failure that, via a relay, directly connects VHF1 to the commander's side, and VHF2 to the co-pilot's side.

Transponder

G-NPTF is fitted with two transponders which transmit the aircraft's identity for the purposes of conspicuity. ATC 1 is powered by DC EMER Bus and ATC 2 is powered by DC Bus 2. ATC 2 was the transponder in use during the incident flight.

Radio altimeter

The radio altimeter provides height information when the aircraft is flying below 2,500 ft. The system consists of two antennas (transmit and receive) and a transceiver. The transceiver is powered by DC Bus 1 and provides height information inputs to aircraft systems including the FDR, EGPWS, and Symbol Generator Units (SGU).

On-aircraft testing conducted by the aircraft manufacturer identified a control signal link between the radio altimeter and SGUs. When the SGU restarts following a power loss, it commands a test signal to the radio altimeter. This test signal results in a low altitude output from the radio altimeter that is transmitted to its linked systems.

EADI and EHSI

The EADI and EHSI on both commander's and co-pilot's sides are Electronic Flight Information Screens (EFIS). The commander's EADI and EHSI are both powered by the DC STBY bus. The co-pilot's EADI and EHSI are both powered by DC Bus 2. The display signal input to the screens is provided by SGUs: SGU1 (powered by the DC STBY bus) for the commander, and SGU2 (powered by DC Bus 2) for the co-pilot.

Aircraft examination

Two faults had been logged on Built-in Test Equipment (BITE) 'doll's eye' magnetic latching indicators; one on the BPCU 'CNTR' (contactor fault) indicator, and the MFC fault indicator on the co-pilot's maintenance panel. It could not be determined if the faults were logged as a result of the incident, as it was not possible to determine when the indicators had last been checked.

Several single-engine ground runs were conducted to fully power all electrical networks on the aircraft. During the second ground run using the No 2 engine, DC GEN 2 FAULT and ELEC captions were observed, together with cycling aircraft power to the co-pilot's instruments. Multiple rapid relay and contactor switching sounds were heard from the location of electrical panels behind the co-pilot's seat during the power cycling. A fault was latched on GCU 2. Following the ground run, GCU 2 passed confidence checks and was interchanged with GCU 1 to isolate any unit fault.

The third ground run using the No 2 engine resulted in the co-pilot's instruments and the commander's EHSI losing power and the BPCU logged another CNTR fault. In-situ examination of the main generator contactors (11PU for DC Gen 1 and 12PU for DC Gen 2) did not reveal any faults.

The subsequent No 1 engine run began with significant relay operation 'chattering' sounds from the panels behind the co-pilot's seat. The chattering stopped after a couple of seconds, and the relays then operated normally for the remainder of the engine run.

The DC Gen 2 was examined in-situ (Figure 8) for signs of external damage or faults, and none were found.

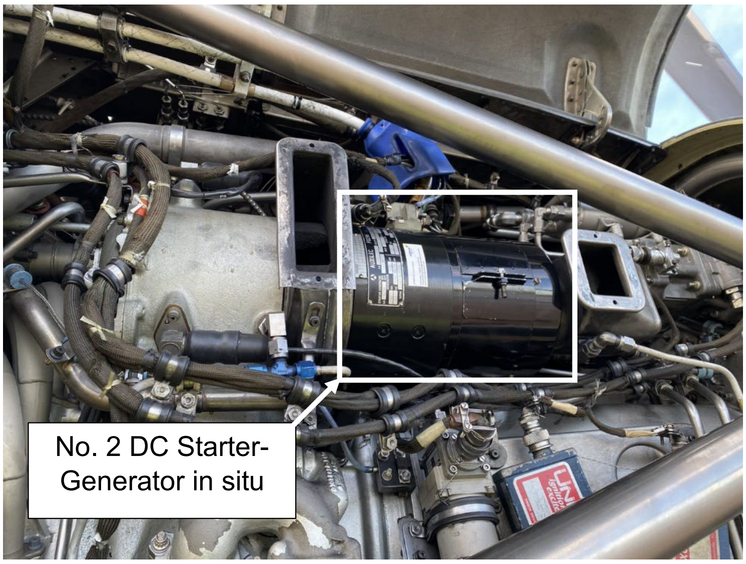

Figure 8
G-NPTF No 2 DC Starter-Generator

Troubleshooting

DC Gen 2 was replaced, and further engine ground runs were conducted. The CNTR BPCU fault reset itself, indicating the fault's causal condition had been removed. No further faults were logged on the GCUs and no other electrical anomalies were observed.

Further troubleshooting using manufacturer maintenance procedures on contactor and relay function, electrical continuity and unit confidence checks were completed, with no faults found.

Tests and research

DC starter-generator

The DC Gen 2 starter-generator removed from G-NPTF was examined by the unit's manufacturer. The examination consisted of a visual inspection, followed by the manufacturer's acceptance test procedure for the unit. Further component-level examination was conducted within the AAIB's laboratories.

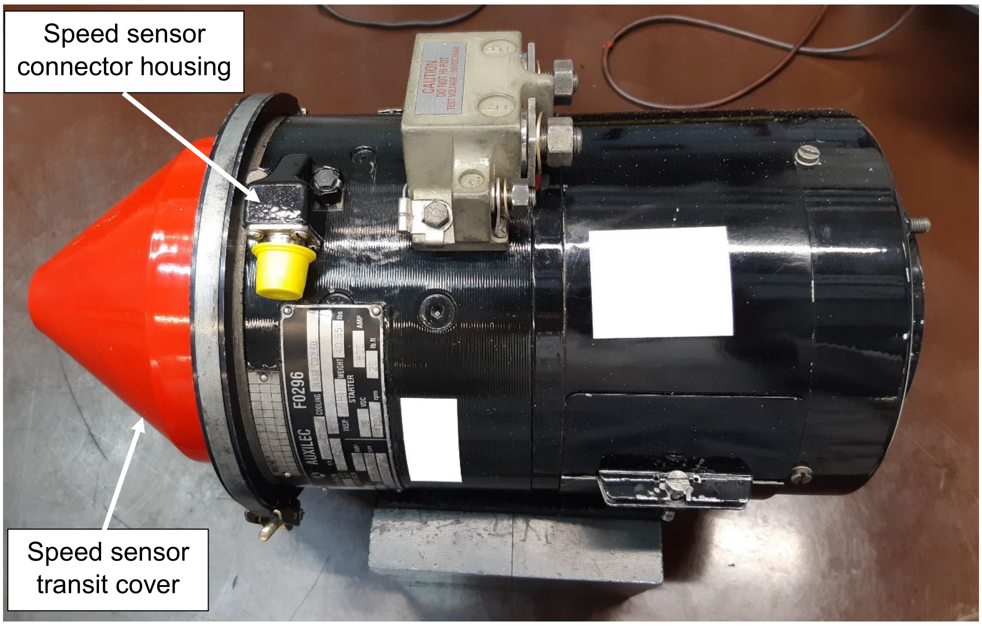

Figure 9

DC Gen 2 starter-generator removed from G-NPTF

<u>Visual inspection</u>

The starter-generator (Figure 9) was visually inspected and considered to be in a satisfactory condition in line with its recent overhaul. There was no sign of external damage of the speed sensor or generator shaft.

The transport cover was removed, and the speed sensor connector and sensor unit were inspected. The speed sensor connector is within a black housing on the outside of the generator casing. It was in good condition, and the pins undamaged. Externally, the cable between the connector and the sensor unit was in good condition and noted to be correctly sealed. Both the speed disc and sensor unit were in good condition.

Acceptance tests

Acceptance tests from the unit's CMM were performed. Shaft spline wear and brush wear were within limits.

Resistance tests of the shunt winding, starter-generator insulation, and speed sensor insulation were all compliant. A resistance test of the speed sensor resulted in an open circuit (infinite measured, criteria 130 Ω ± 10 Ω) and was considered to fail the test.

The starter-generator was mounted to a test rig for dynamic testing where it failed the test due to speed sensor signal measurement. No signal was measured at the beginning of the dynamic test (five minutes); it was then intermittent (one minute), and then recovered and remained stable.

Following the dynamic test, the peak voltage of the speed sensor output was measured separately. The measured value was 1.36 V DC, considered to be able to be adjusted to reach the minimum required specification of 1.4 V DC by reducing the air gap between the speed disc and the speed sensor. This value remained constant during the unit's cool-down over approximately two hours, unaffected by heat.

Speed sensor connector examination

The speed sensor output connector was removed from its housing for examination of wiring condition and further resistance checks (Figure 10). The speed sensor output connector is connected to the sensor unit by two 26 AWG wires, each containing seven strands of 0.15mm diameter.

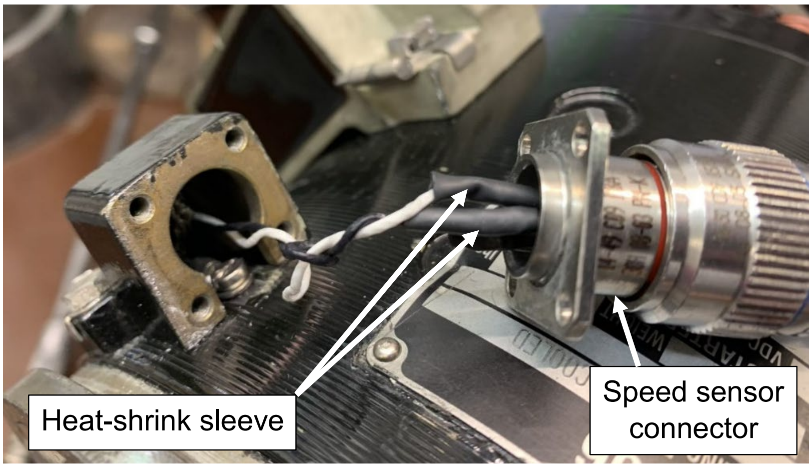

Figure 10

Speed sensor connector and wires

During light manual manipulation of the connector, the resistance measurement fluctuated between the correct value (130 Ω) and open circuit. Activating an open circuit was repeatable through gentle pressure on the speed sensor connector wiring.

The wires are soldered to pins at the rear face of the connector, and the soldered joint covered with heat-shrink sleeve. Removing the heat-shrink sleeve from the white wire showed the wire to be completely broken but, whilst held in place by the heat-shrink sleeve, close enough to make intermittent contact. Removing the heat-shrink sleeve on the black wire showed damage to the wire core (Figure 11).

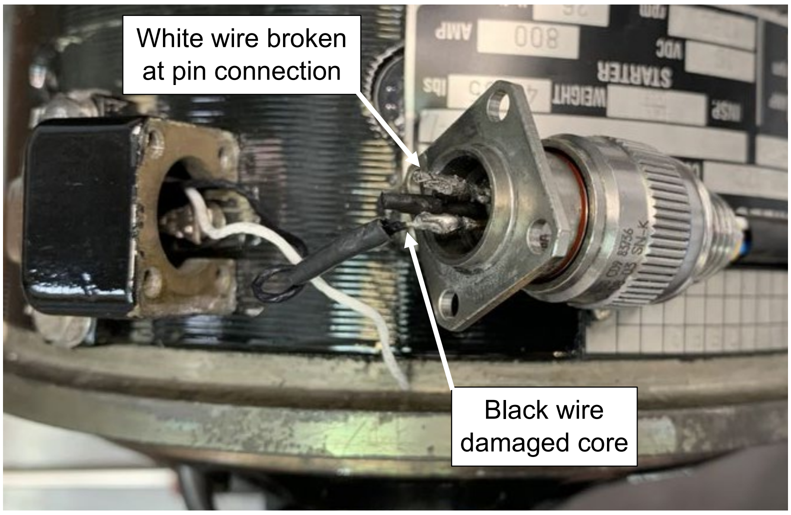

Figure 11

Speed sensor connector with heat-shrink sleeve removed from wires

Speed sensor wire examination

Further microscopy analysis by the AAIB of the white wire showed partial unravelling of the core and breakage damage at the pin connection soldered joint (Figure 12), and evidence of mechanical insulation removal (Figure 13).

Figure 12

Speed sensor connector soldered pin and broken white wire conductors

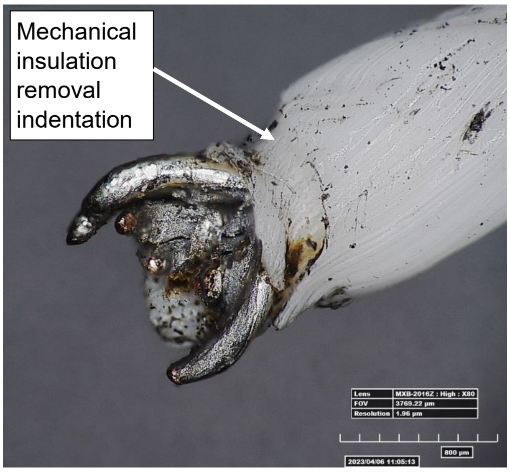

Figure 13

Speed sensor white wire broken conductors

The core of the black wire had two broken strands at the soldered pin joint and evidence of mechanical insulation removal (Figure 14).

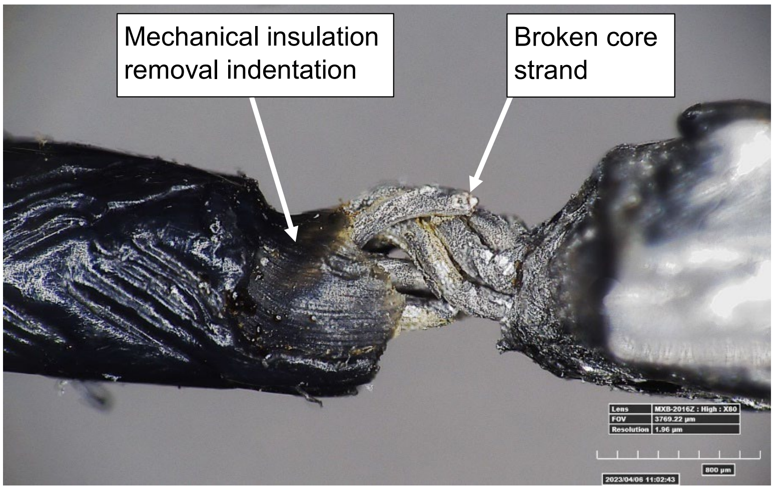

Figure 14

Speed sensor black wire damaged core at connector pin

Speed sensor removal

The manufacturer's overhaul and maintenance procedure requires removal of the speed sensor connector from the wires to facilitate cleaning of the main generator unit. Excess wire length is provided at manufacture, to allow this to be performed multiple times during the unit's service life. To reconnect the wires, a small portion of the wire's insulating outer sleeve is removed to expose the wire core before soldering to the connector pins.

The starter-generator was overhauled, in accordance with the manufacturer's CMM, at a third-party provider. The type of tool required to strip wire insulation is not specified within the CMM and the provider used a standard mechanical stripping tool (Figure 15). To strip the insulation, a wire is inserted through the correct gauge for the wire in accordance with the markings on the tool. The tool handles are squeezed together, and this action clamps the wire whilst the two cutters (shown on the right of Figure 15) close to cut the insulation to the correct depth and then strip it from the wire. Misalignment of the wire with the correct wire gauge on the tool will result in either the insulation not being stripped, or the conducting wires being part-severed by the two cutters as they come together.

Figure 15
Mechanical wire stripping tool used at overhaul

In contrast to the third-party provider, the manufacturer of the starter-generator confirmed that it uses thermal insulation stripping tools (Figure 16) in its facility as it had previously observed the potential for wire damage by using mechanical tools.

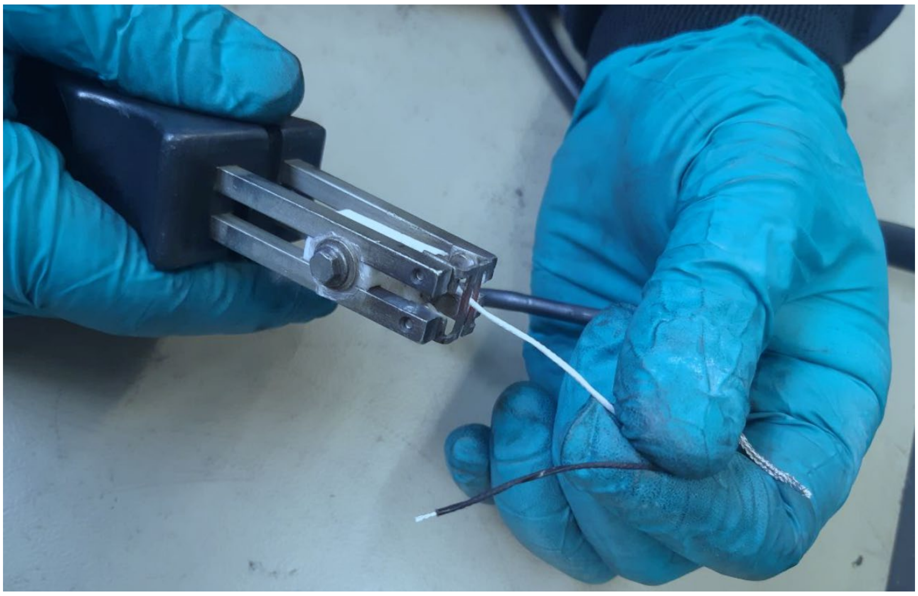

Figure 16
Thermal wire insulation stripping tool

MFC BITE memory

The BITE memory data from both MFCs was downloaded and analysed by the manufacturer.

Some data from the MFC BITE could be attributed to the event as it is logged against a 'flight', which is the period of time between two takeoffs. Although the BITE data does not indicate when, or for how long a condition persisted, or whether there were multiple instances detected within a 'flight', analysis of this data shows system or sensor failures which are consistent with losses of the following electrical buses: DC ESS Bus, DC STBY Bus, DC Bus 2, DC UTLY Bus 2, and 26V AC STBY Bus and/or 26V AC Bus 1.

Analysis

Conduct of the flight

The crew had reported for duty at 2320 hrs and the incident began approximately four hours later. Both crew members said they felt well-rested and that their roster was not unduly challenging, and so fatigue is not considered to have been a factor.

The event began with the aircraft in cloud at low altitude, carrying out a CAT II approach. In accordance with the company operations manual, when the malfunction occurred below 1,000 ft aal, the crew initiated a go-around. As the aircraft began the go-around, the crew were presented with a significant loss of flight instrumentation and multiple visual and audible alerts including ground proximity warnings. This resulted in a high workload for the crew, but their initial focus was to assure a safe flight path for the aircraft and so prioritised this, and then communications, over any diagnosis of the malfunction. As the commander's EADI and EHSI went blank for a few seconds, he reverted to the functioning standby instruments for flight path information.

They established the aircraft in the climb and followed the published standard go-around procedure. Due to the likely distraction caused by the many warnings, the crew did not initially retract the flaps. Once level at 3,000 ft, the crew recognised the miss-set flaps and retracted them; flap limiting speed was not exceeded.

At this point, the co-pilot had no reliable flight instruments, and this disrupted the usual crew resource management as his ability to monitor the aircraft's flight path was significantly degraded. In addition, as the crew were unable to select AP, the commander had to fly the aircraft manually and this added to his higher than normal workload.

Once the aircraft reached the go-around altitude of 3,000 ft amsl, the crew made a PAN call to ATC. The crew did not get a response to this call or to their request for radar vectors toward Birmingham Airport. Concerned that they now also had a communications failure, they continued the published go-around procedure and turned right towards the hold at the EME beacon.

In an attempt to resolve the communications issue, the crew changed frequency to 121.5 MHz, the distress frequency. Again, they received no response and so returned to the EMA Tower frequency. With the prospect of a manually flown diversion, using degraded flight instruments and without radio communications, crew workload was high. They made a MAYDAY call to EMA Tower and, in the static, believed they heard a response directing them to contact EMA Approach. They did so and, on that frequency, re-established clear communications and asked for vectors toward Birmingham.

Once the go-around procedure was complete and the crew had re-established radio communications, they gave more attention to addressing the malfunction. Whilst the many warnings and the loss of flight instruments and communications were not consistent with a failure of just a generator, the first indications the crew had noticed were the ELEC and DC GEN2 captions. They therefore decided to action the QRH procedure for a DC GEN2 fault. With the DC GEN 2 switched off the warnings ceased. As the BTC did not close, due to cycling three or more times within two seconds and entering into a lock-out condition, the co-pilot's side of the cockpit remained unpowered. The BTC could have been reset (as the cause of the lock-out was no longer present) by cycling the BTC pushbutton switch located on the flight deck overhead DC electrical panel. The crew were unaware of this as the conditions that trigger a BTC lock-out are not detailed in the FCOM. However, the system reset is described in the FCOM and QRH. Due to the loss of the ADU, the crew were unable to select any autoflight functions. The resulting aircraft configuration precluded making a CAT II approach, so the crew continued with the diversion to Birmingham, where the weather was suitable for a CAT I approach, with the commander manually flying the aircraft and the co-pilot monitoring.

Prior to landing at Birmingham, the crew reviewed the DC Bus 2 Lost Equipment List and took appropriate action, including cross-feeding hydraulic systems, to manage the issues. The crew workload load was higher than normal due to the lost systems, but the crew managed the diversion effectively and the aircraft subsequently landed without further incident.

Starter-generator wiring damage

The partially-connected, damaged wiring at the speed sensor connector pin joints resulted in a rapid, intermittent speed measurement signal being sent to the GCU. The GCU interpreted this as a fault and indicated a DC GEN2 caution to the crew. It also led to the electrical system GCU rapidly opening and closing contactor 23PA causing power fluctuations and "flashing" of displays.

The appearance of the insulation on both connector wires at the soldered joint end is indicative of a mechanical cutting-type insulation stripping tool being used during the unit's previous overhaul process and this was confirmed by the overhaul provider. It is possible to damage the internal core with this type of tool if the wire is misaligned with the correct wire gauge on the tool, and it is probable that this is how the damage occurred.

The manufacturer of the starter-generator had previously identified the risk of mechanical damage from mechanical insulation stripping tools and uses thermal wire strippers in its own manufacturing and overhaul facility. However, the use of these tools was not specified in its product maintenance documentation.

Consequential loss of aircraft systems

A review of the flight data provided no indication as to why the speed sensor wire failed when it did, but it came at a critical time during the latter phases of a CAT II approach in reduced visibility at night. Due to the rapidly changing and unusual power distribution configuration of the aircraft during this event, it has not been possible to fully explain the behaviour of some of the flight instruments that was observed by the crew and that of other aircraft systems.

Loss of electrical networks

As a consequence of the damage to its speed sensor wire, the speed signal output from DC Gen 2 was intermittent. This meant that the GCU received cyclic input signals indicating that DC Gen 2 was operating below 61.5% NH and therefore not as a generator. In response, the GCU opened and closed the main generator contactor for DC Bus 2 in rapid succession to match the input, leading to DC Bus 2 receiving rapid fluctuations in power.

When power is lost to DC Bus 2, the aircraft's systems reconfigure the power networks to supply DC Bus 2 from DC Bus 1, via the BTC. However, as the power was lost and regained rapidly, the BTC locked open in a self-protection mode, having been cycled three or more times within two seconds. A BTC lock-out can be reset by cycling the pushbutton switch, as long as the cause of the lock-out is no longer present. This requires the crew to have recognised the conditions for a lock-out.

DC Bus 2 continued to receive rapidly cycling power from the DC Gen 2 until it was isolated by the crew. This action stabilised the electrical systems by disconnecting DC Bus 2 and UTLY Bus 2, and the emergency power network reconfigured to supply DC ESS Buses on DC Bus 1 via the 1PA and 3PA contactors.

The flight systems and instrumentation observed to have been lost indicate that the following electrical supply behaviour occurred:

- A rapid cyclic loss of supply to DC Bus 2 before DC Gen 2 was isolated
- A loss of supply to DC Bus 2 after DC Gen 2 was isolated
- Transient loss of supply to DC ESS Bus during emergency power network reconfiguration
- A transient loss of supply to DC STBY Bus
- Automatic load shedding of DC UTLY Bus 2
- A loss of supply to AC Bus 2 via its inverter

The main aircraft battery was seen to be discharging following the isolation of DC Gen 2 for the remainder of the flight, but it was not possible for the AAIB or aircraft manufacturer to ascertain the reason for this.

Loss of flight instruments

The co-pilot's EADI, EHSI and SGU2 are powered by DC Bus 2. Their irregular behaviour and then total power loss can be explained by the intermittent and then full loss of DC Bus 2.

The signal input to the commander's EADI and EHSI is supplied by SGU 1 which is powered by DC STBY bus. The MFC BITE data analysis showed that there was a loss of the DC STBY bus at some point during the recorded 'flight' event. It is possible that the loss of the DC STBY bus could have disrupted the power input to the EADI and SGU1, resulting in blank screens whilst the SGU restarted. However, this cannot be confirmed as the BITE failure logged could have occurred at any time between the previous and the following take-off and this includes on-ground testing conducted after the event. It was not possible to confirm a direct link between the loss of the DC STBY Bus and the speed sensor output signal failure.

The co-pilot's ASI is powered by AC 2. The AC 2 network was not recovered following loss of supply to the AC inverter from DC Bus 2. The co-pilot's ASI did not regain power, indicating that the AC BTR did not close. It was not possible to ascertain why the BTR did not close as it should have automatically done so despite the BTC entering a locked-out state.

Loss of VHF communications

Each time DC Bus 2 was lost, voltage drops occurred whilst DC ESS Bus power supply was reconfigured within the aircraft's emergency electrical network. The RCAU is normally powered by DC ESS Bus and therefore was subject to power fluctuations causing the RCAU to enter a fault mode where the commander's headset was 'locked' to VHF1 and the co-pilot's headset to VHF2. The power cycling led to RCAU internal relay 'chatter', causing temporary losses of VHF communications through audible interference. Once the electrical network was stabilised after DC Gen 2 was switched off, VHF communications were available to both crew.

Radio altitude data

The low radio altitude data outputs seen during the flight were consistent with the co-pilot's SGU restarting after each cyclic loss of DC Bus 2 power and commanding a test signal to the radio altimeter. The data returned to normal once DC Gen 2 was switched off.

EGPWS warnings

EGPWS warnings were consistent with the system working correctly but receiving spurious radio altitude data inputs. The warnings ceased when the DC Gen 2 was switched off and radio altitude data returned to normal.

Conclusion

A wiring defect on the DC Gen 2 speed sensor resulted in rapidly changing erroneous signals being sent to the GCU. This resulted in the rapid opening and closing of contactor 23PA in response to these inputs and, due to the rapidly fluctuating conditions, the BTC entered a self-protection mode and remained open for the remainder of the flight.

As a consequence of the above, the crew lost a significant number of instruments and systems during the final phases of a CAT II approach in reduced visibility at night. The power distribution anomalies also resulted in a number of spurious and potentially distracting EGPWS aural alerts. The crew conducted a go-around and, following a temporary loss of communications and permanent loss of autoflight capability, manually flew the aircraft to Birmingham Airport where it landed without further incident.

The wiring defect was probably caused by incorrect use of wire stripping tools at the third-party organisation that had overhauled the starter-generator.

The starter-generator manufacturer and the overhaul organisation have identified a number of safety actions they intend to take to prevent a reoccurrence.

Safety action

Following this occurrence, the starter-generator manufacturer has stated it will be taking the following safety actions:

- To modify the CMM procedure for this unit to highly recommend the use of thermal wire strippers.
- Extend the use of thermal wire strippers to all other applications.

The overhaul facility has stated it has taken the following safety actions:

- An analysis of standard practice manuals to check the method of wire stripping specified, followed by an update of the relevant Technical Instruction to bring it in line with the standard practices.
- Clarified that tool choice is performed in the following order for each task: CMM, Standard Practice, Technical Instruction.
- The Method Department technicians have been informed of the issue and, where a method is not specified, they will assist the technician in assessing the best way to strip the wire.
- Wire stripping has been declared as an industrial process and training is to be performed.
- Technicians have been informed that the preferred method of wire stripping is to use thermal wire strippers.

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