Serious Incident

Aircraft Type and Registration:	ATR 72-212A 600, EI-GPN
No & Type of Engines:	2 Pratt & Whitney PW127 turboprop engines
Year of Manufacture:	2015
Date & Time (UTC):	19 September 2022 at 1100 hrs
Location:	Belfast City Airport
Type of Flight:	Commercial Air Transport
Persons on Board:	Crew – 4 Passengers – 32
Injuries:	Crew – None Passengers – None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	40 years
Commander's Flying Experience:	3,900 hours (of which 3,200 were on type) Last 90 days – 164 hours Last 28 days – 50 hours
Information Source:	AAIB Field Investigation

Synopsis

During the aircraft's approach to Belfast City Airport, a number of aircraft systems dropped off-line including some necessary for landing. The flight crew, experiencing natural effects of startle and surprise, and without a specified procedure to follow, continued with the approach, restoring systems by turning off the Transformer Rectifier Unit (TRU). The aircraft was operating under an Operations Engineering Bulletin[1] (OEB) which required the TRU to be continually powered. Following the failure of an electrical contactor, this disconnected the DC output from the TRU to the Standby and Emergency bus bars, thereby removing electrical power to several aircraft systems.

The aircraft manufacturer has taken safety action to improve the guidance for flight crew in the event of a contactor failure when operating under the OEB. In addition, they have introduced a modification which, when embodied, removes the requirement to operate with the TRU permanently powered.

The operator intends to adopt a rule-based method for managing startle, which can help pilots manage workload and maximise their situation awareness before flying an approach.

Footnote

1 Initiated by EASA Emergency Airworthiness Directive E-AD 2021-0120-E.

History of the flight

Background information

An *'Operations engineering bulletin'* (OEB)[2] (Figure 1) required the aircraft to operate with the TRU ON.

Potential temporary loss of all Cockpit Display Systems

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MSN 1087 / 1097 / 1105 / 1107 / 1169 / 1300 / 1315 / 1322 / 1324 / 1326 / 1334 / 1339 / 1464 / 1471

Procedure

To prevent the temporary loss of all Cockpit Display Systems (including IESI), the TRU must be set **ON** during the "Before Taxi" Procedure and must be set **OFF** during the "After Landing" Procedure.
Use of "BEFORE TAXI" and "AFTER LANDING" Electronic Check Lists is prohibited.
The flight crew must use the QRH
The flight crew must apply :

Normal Procedure:

- **BEFORE TAXI NORMAL PROCEDURE**
  - ▶ TRU.. .... ON & CHECK
- **AFTER LANDING NORMAL PROCEDURE**
  - ▶ TRU.. .... OFF

Normal Check list

- **BEFORE TAXI CHECK LIST**
  - ▶ TRU.. .... ON & CHECK
- **AFTER LANDING CHECK LIST**
  - ▶ TRU.. .... OFF

Figure 1
OEB 56 from the Quick reference handbook

First flight

The crew were scheduled to operate the aircraft from Belfast City Airport (Belfast) to Leeds Bradford Airport (Leeds) and back, then Belfast to Edinburgh Airport (Edinburgh) and back.

The aircraft departed Belfast at 0555 hrs with enough fuel to complete the first three flights[3]. Later, while descending to FL110 inbound to Leeds, a master caution message appeared very briefly, with no associated symptoms. Believing it to be ELEC SBY UNDV, the commander (who was PM), reviewed the relevant procedure in the Quick reference handbook (QRH) (Figure 2). Just after touchdown at 0641 hrs, the same master caution message briefly illuminated, long enough to confirm he had identified it correctly.

Footnote

[2] OEB – contains technical information and temporary procedures to address relevant deviations from initial design objectives.
[3] Fuel can be carried for subsequent flights for economic reasons.

DC STBY BUS UND-V | **A24.17**

- **If DC GEN 1+2 operate**
  - **If one ACW GEN lost**
    - ▶ HYD BLUE PUMP..OFF
    - ▶ HYD X FEED..ON
  - ▶ TRU..ON
  - **If STBY BUS UND/V disappears**
    - ▶ TRU : KEEP ON

    MAINTENANCE ACTION REQUIRED
  - **If STBY BUS UND/V persists**
    - ▶ TRU.. OFF
    - ▶ HYD X FEED ....OFF AS RQRD
    - ▶ HYD BLUE PUMP..ON AS RQRD
    - ▶ DC STBY BUS FAILURE procedure (A24.16) .... APPLY
- **If DC GEN 1+2 FAULT and TRU not available**
  - **For approach only**
    - ▶ DC STBY BUS..SELECT OVRD

Figure 2

DC standby bus undervoltage QRH procedure

After parking the aircraft and shutting down its engines, the commander telephoned the operator's airworthiness engineer who suggested powering down the aircraft's electrical system by way of a "re-set". The commander reviewed the aircraft's Minimum equipment list (MEL)[4] to assist with his decision making. He reported the engineer called back with questions about the symptoms of the fault, advising him the underlying cause could be difficult to establish. Therefore, given the transient, asymptomatic nature of the master cautions and the absence of company engineering support in Leeds, they agreed the crew would operate the aircraft back to Belfast for company engineers to investigate further. Both pilots agreed to monitor the electrical system and cancel the departure should any abnormalities occur.

Incident flight

At approximately 0815 hrs, while climbing through FL095 after departing Leeds, the same master caution message occurred for a few seconds. The commander, who was PF, asked the co-pilot to display and monitor the ELEC system display (SD) page on his multifunction display (MFD)[5] (Figure 3), discussing his intention to ground the aircraft on arrival. The co-pilot transmitted blind to the operator on VHF2, by which time they were near the Isle of Man.

Footnote

[4] Had the fault latched, the MEL specified *'No dispatch'*.

[5] MFD – can display several formats including system display pages or navigation display.

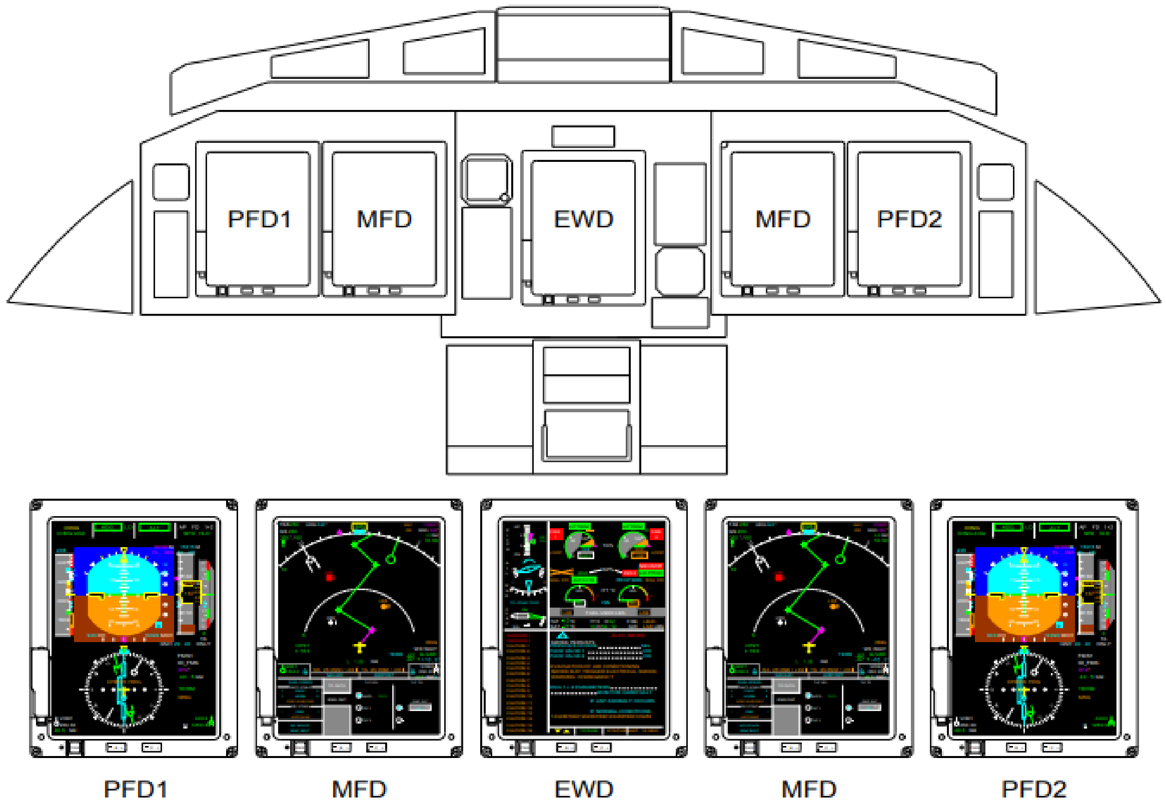

Figure 3
Display unit layout

No further abnormalities occurred until around 0850 hrs when the aircraft was descending through FL82 to altitude 4,000 ft, towards Belfast Runway 22 ILS approach. Recorded data showed a master warning was triggered, and the autopilot (AP) and yaw damper (YD) disengaged. Both pilots recalled some electrical busbars turning amber on the SD page. The flight director (FD) command bars disappeared from their primary flying displays (PFDs), the selected altitude reduced to zero, and the heading bug jumped 180° away from its original position.

Still descending, the crew re-selected cleared altitude 4,000 ft and re-engaged the FD modes, AP, and YD. However, they disengaged again, and multiple failures appeared on the engine warning display (EWD). The flight crew reported believing those included DC STBY BUS UNDV, although the commander recalled the associated ‘UNDV’ pushbutton light on the overhead panel was not illuminated. On hearing the engines’ propeller speeds increase unexpectedly, the commander asked the co-pilot to move the condition levers to 100% OVERRIDE. Another master warning occurred which the co-pilot announced “LANDING GEAR NOT DOWN”. Normal pitch trim control stopped functioning such that “a lot of force” was required by the commander to decrease the rate of descent. FAIL flags appeared on the co-pilot’s ASI, altimeter, and vertical speed indicator (VSI). The commander recalled his ASI speed bugs disappeared, and his navigation display (ND1) switched from ARC to ROSE mode, and increased range. Using the ‘standby instrument’[6]

Footnote

[6] Integrated electronic standby instrument.

and compass, the commander confirmed his remaining PFD information was reliable. The co-pilot continually provided effective monitoring calls about the aircraft's flight path and configuration.

The commander asked the co-pilot to transmit a PAN call to ATC but VHF 1 along with transponder 1 had failed. By the time the co-pilot transmitted it on VHF2, ATC were simultaneously calling the aircraft, having lost SSR contact. The co-pilot reported he was unable to scroll through or select the EWD list of alerts[7], commenting "CAN'T GET ANY OF THESE CHECKLISTS" (Figure 4). Both pilots subsequently reported the screen, including engine instruments, appeared "frozen"[8]. The commander asked the co-pilot to check the circuit breakers and tried unsuccessfully to re-engage the FD modes, AP, and YD.

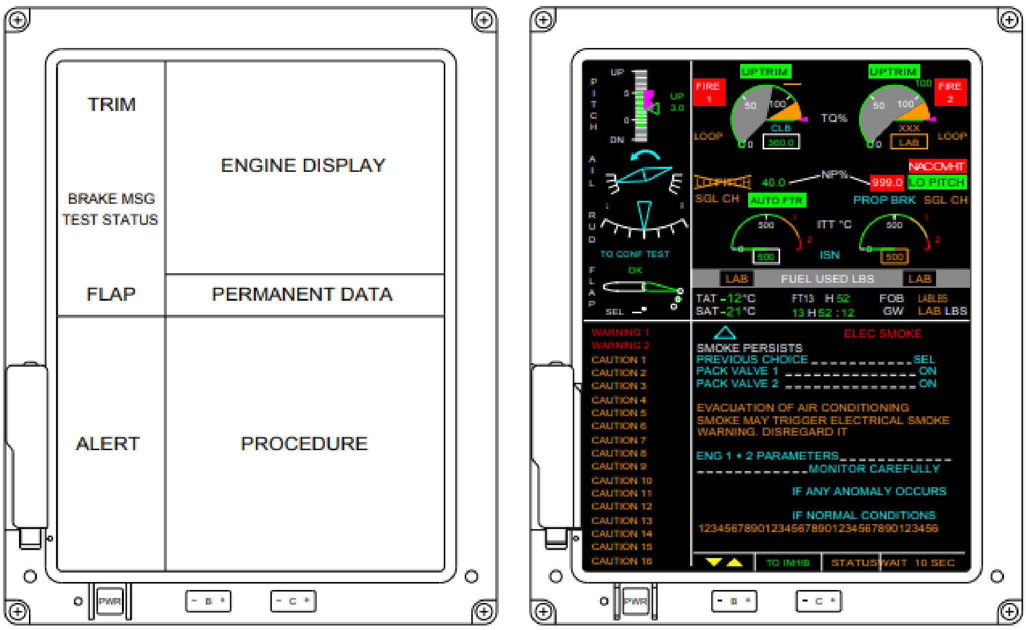

Figure 4

Example Indications on EWD from Flight crew operating manual
(not a representation of the indications presented during the incident)

ATC instructed the crew to fly a heading of 290° and descend to an altitude of 2,000 ft, with 16 nm to touchdown. The commander called the senior cabin crew member to the flight deck for a NITS briefing[9]. Recorded data showed a spurious master caution sounded while the aircraft's electrical network attempted to reconfigure after the DC EMER BUS temporarily recovered.

Footnote

7 A pilot uses their EFIS control panel to select an ALERT, displaying its associated PROCEDURE.
8 The commander said he was "almost certain" the TRQ, NP and NH indications were not functioning.
9 NITS – Nature of situation, Intentions, Time available, and Special instructions.

While on a heading to intercept the localiser, the crew were cleared for the approach. However, realising they had no ILS indications, they requested a visual approach instead. The commander announced they were low on profile and levelled the aircraft at around 1,600 ft amsl before gradually climbing back to around 1,900 ft amsl. Around 8 nm from the runway the crew selected FLAP 15 then landing gear down but neither deployed. The primary landing gear position indicators had stopped working so the co-pilot announced three landing gear UNLK indications on the overhead secondary panel. He reported the only other overhead lights illuminated were the TRU ON and its associated arrow light (Figure 5). The commander asked the co-pilot to check the hydraulic system indications.

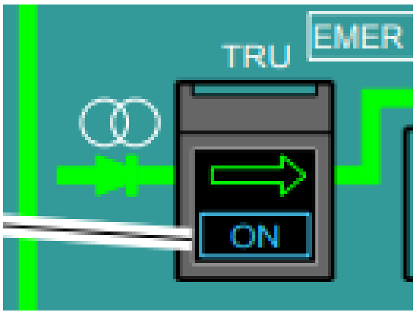

Figure 5

TRU pushbutton on overhead 'Main electrical power' panel

Around 6 nm from the runway, the crew were transferred to Belfast tower frequency. They discussed performing the *'Landing gear gravity extension'* procedure, realising they would need to discontinue the approach to have enough time to do so. However, the commander recalled believing the already difficult nose-down pitch control forces might become problematic during a go-around.

The commander reported that while considering how to resolve the failure, he still had the TRU in mind from earlier on. At 0856 hrs and around 1,900 ft amsl, he instructed the co-pilot to select TRU OFF. Immediately, the display units and normal pitch trim control returned; the landing gear and flaps deployed. The commander reported being right of the runway track with four white 'precision approach path indicator' (PAPI) lights[10] visible. The crew selected FLAP 30, performed the *'Before landing checklist'*, and were cleared to land. The co-pilot stated "ONE THOUSAND ABOVE YOUR SPEED IS GOOD". The aircraft's rate of descent peaked at just over 1,000 ft/min and at 500 ft agl the commander announced he could see two red and two white PAPI lights. The aircraft landed at 0859 hrs.

Weather information

The Belfast weather was reported at 0820 hrs as wind 3 kt from 210°, visibility more than 10 km, no clouds detected and temperature 14°C.

Footnote

[10] Two red and two white PAPI lights indicate the aircraft is on the glideslope. More white lights means the aircraft is high and more red lights means it is low.

Recorded information

EI-GPN was equipped with a solid-state FDR and CVR, capable of recording 2 hours of audio and 25 hours of flight data.

On the flight before the incident flight, as EI-GPN started to descend towards Leeds, the CVR recorded the sound of a master caution. The FDR data showed that the voltage on the DC EMER BUS dropped briefly, from 28 V[11] to 20 V, and that the DC STBY BUS dropped momentarily off-line. On landing, the sound of another master caution was recorded by the CVR, the FDR recorded a brief drop of DC EMER BUS voltage and the crew remarked on the reoccurrence of the electrical problem experienced earlier in the flight. No other voltage transients, or loss of DC buses, were seen on any of the preceding flights recorded by the FDR.

On the return flight to Belfast, at 0814:14Z, as EI-GPN climbed through FL95, the CVR recorded the sound of a master caution and the FDR data showed that the DC STBY BUS dropped momentarily off-line.

Thirty-five minutes later, at 0849:15Z, as EI-GPN descended towards Belfast passing through FL82, a master warning was triggered, and the AP and YD disengaged. The FDR data showed that the loss of AP and YD functionality, see point A on Figure 6, was coincident with a voltage drop on the DC EMER BUS and loss of the DC STBY bus, as had occurred on the previous flight, but both buses recovered quickly. The AP and YD were then re-engaged by the crew.

Twenty-eight seconds later, at 0849:43Z, a further master warning was generated as the AP and YD disengaged again (point B), and the DC EMER BUS and DC STBY BUS dropped off-line. Simultaneously, the propeller speed for both engines increased towards 100%[12], as the propellers' governors were affected by the reconfiguration of the aircraft's electrical network caused by the loss of the buses. The radio altimeter signal also became invalid and the change in status of this signal triggered a master warning, associated with the landing gear not being selected down, as this alert relies upon the radio altimeter to sense proximity to the ground. However, unlike the previous occurrences, the DC EMER BUS and DC STBY BUS did not recover and both buses then remained unpowered for the next four and half minutes.

Footnote

[11] 28 V is the nominal voltage of the DC buses on the ATR72-212A.

[12] The propeller speed for both engines thereafter remained at 100%, as the crew manually re-positioned the propeller condition levers to 100%.

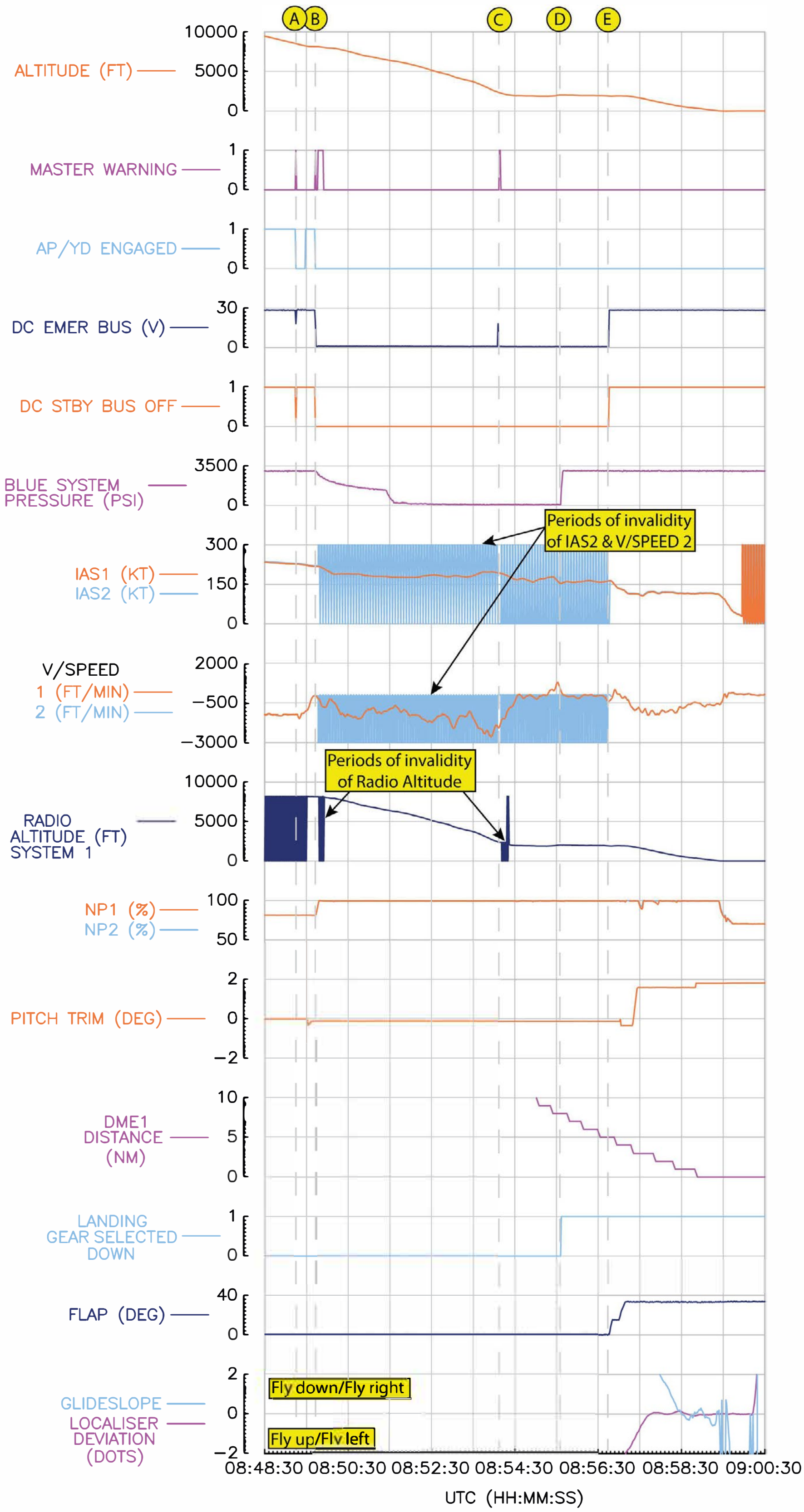

Figure 6

Flight data for the incident flight from just prior to the loss of AP and YD, until after landing.

The FDR data showed that throughout this time, as the crew continued their approach towards Belfast (Figure 7), the functionality of several systems was lost. These included:

- The co-pilot's air data computer (ADC); this resulted in no airspeed, altitude, and vertical speed data displayed on the co-pilot's PFD[13],
- the blue hydraulic system required for flap extension and the roll spoilers,
- the normal pitch trim system[14],
- the normal landing gear extension system,
- some secondary engine instrumentation for the left engine,
- VHF radio number 1 and the transponder.

Figure 7

Approach towards Belfast from just prior to the loss of AP and YD, until after landing.

At 0854:06Z, as EI-GPN descended through 2,400 ft amsl with approximately 12 nm to run to Belfast, the voltage of the DC EMER BUS recovered momentarily (Figure 6 point C), and then dropped again. This resulted in a further spurious master warning, associated with the landing gear not being selected down, as EI-GPN's electrical network attempted to reconfigure. However, both the DC EMER BUS and DC STBY BUS remained unpowered for a further 2½ minutes.

Footnote

13 The Commander's ADC remained operational, but this was not selected for display on the co-pilot's PFD.

14 The standby pitch trim system remained operational, but the FDR data showed that the stabiliser's position did not change during the loss of power to the DC buses.

At 0855:37Z, approximately 8 nautical miles from touchdown, and passing through 2,000 ft amsl, the crew selected the landing gear down (Figure 6 point D). However, the sound of the landing gear travelling was not recorded until passing through 1,900 ft amsl at 5 DME, when the crew turned off the TRU at 0856:45Z (point E). This action restored power to all the affected DC buses, however, the blue hydraulic system had already re-pressurised on selection of the landing gear down.

Shortly afterwards, at 0856:47Z, landing flap was selected and EI-GPN decelerated from 160 kt to 120 kt. During the latter stages of the approach, for periods of up to several seconds at a time, the descent rate exceeded 1,000 ft/min. EI-GPN landed safely at 0859:29Z.

Information from the operator

The operator commented that selecting the TRU on usually involved “substantial switching” which could affect other systems. It queried using an emergency back-up system for lengthy periods during normal operations.

After the incident, the operator released a ‘Safety notice’ to its flight crew, explaining what happened and asking them to report any electrical anomalies. Some days later the advice was formalised in a *‘Temporary flight crew instruction’* which stated:

> *‘Effective immediate. Any momentary losses of electrical equipment or loss of EMER, ESS, or STBY BUSSES must be entered in the tech log and ACE contacted immediately.*
>
> *In addition, if flight crew experience a temporary indication of undervoltage on the overhead panel, no matter how momentary, it must be entered in the tech log and ACE contacted immediately.*
>
> *For any such events, flight crew must also submit a SMS[15] 360 report.’*

Having recreated the incident conditions in its own simulator session, the operator indicated the failure symptoms were challenging and observed that OEB 56 did not include an abnormal procedure to identify, troubleshoot and resolve the failure.

The operator stated its intent to maximise learning from the event.

Additional information from the flight crew

The commander explained some complexity in applying the *‘DC STBY BUS UND-V’* QRH procedure during the first flight. Relevant conditions required the TRU to be selected ON, whereas it was already ON under OEB 56. With that still in his mind while considering how to resolve the failure during the incident, the TRU’s illuminated indications (Figure 5) prompted him to turn it OFF. He described preferring to return the aircraft to, what he called, its “original design” – meaning its electrical configuration prior to the release of OEB 56.

Footnote

15 Safety management system.

The CVR showed characteristic effects of startle, surprise and stress in the flight crew's communication and information processing while the failure unfolded. With no clear cause, or procedure to follow, the commander reflected on the strength of startle effect during a real failure compared with simulator training. He stated "the aircraft had a lot of failures, including the system which tells you what failed". He said the high pitch control forces made it "just about manageable to fly the approach". It did not occur to him at the time to use standby pitch trim control. He reported the co-pilot's instrumentation failures meant that passing control of the aircraft to him did not seem like a good option. Reflecting on a previous simulator training session during which an electrical fault caused smoke in the flight deck, the commander had wanted to land EI-GPN as soon as possible.

The co-pilot described his PFD and MFD had "red crosses everywhere". He was particularly surprised at being unable to access the EWD procedures using his EFIS[16] control panel (EFCP-R), commenting "I remember pushing the buttons hard and returning to it at least a couple of times as I found it hard to believe it was not working… it seemed… the screen just froze, and the checklists were never going to work no matter what buttons I pressed or how hard I pressed them". He was fairly, though not completely, sure he tried the commander's EFCP-L without success.

CVR evidence indicated supportive and intuitive teamwork between the crew.

Additional information from the operator's Operations manuals

The operator's Operations manual Part B (OMB) contained the operator's *'Stabilised approach criteria'*. Relevant parts include:

> *'An approach is considered stabilised when all of the following conditions are met.*
>
> - *The aircraft is on the correct flight path.*
> - *Only small changes in heading or pitch are required to maintain the correct flight path.*
> - *The aircraft is in the correct landing configuration.*
> - *All checklists and briefings are complete.*
> - *The aircraft speed is Vapp (with wind corrections) +10kts/-0kts.*
> - *Descent rate is less than 1000 ft/min (if the approach requires a higher descent rate, this must be covered in the briefing).*
> - *Power is set correctly, according to aircraft weight and conditions…*
> - *The visual segment of any approach must be flown with reference to the PAPIs, where available, to within not more than one light deviation high or low.'*

Footnote

[16] EFIS - Electronic flight instrument system.

OMB specified an aircraft must be stabilised by *'500ft. aal'* although the operator reported that had recently changed to 1,000 ft aal. Otherwise, a missed approach must be performed.

OMB stated *'Pilots should use the TDODAR decision-making process to manage abnormal occurrences'.* It stands for *'Time… Diagnosis… Options… Decision… Assign/Action Tasks… Review and Risk Assessment'.*

Aircraft description

The Avions de Transport Régional (ATR) 72-212A-600 is a short-haul twin turbo-propeller passenger aircraft. The aircraft can carry up to 72 passengers and has a MTOW of 23,000 kg with a range of 1,500 km. The 600 series ATR aircraft are fitted with fully integrated digital cockpit displays including the single integrated electronic standby instrument (IESI). It also has a full authority automatic flight control system and ILS.

Aircraft electrical power supply and distribution system

The aircraft electrical power requirements are supplied by the following:

- Two 24 V DC nickel cadmium batteries (main and emergency) which supply the critical DC electrical loads in flight should the DC generated supplies be lost. They have the capacity to sustain up to 30 minutes of power to essential systems. The main battery supplies power for engine start.
- Two 28 V DC starter generators driven by the accessory gearbox on each engine.
- Two Static Inverters are supplied with DC Power to produce 26 VAC & 115 VAC constant frequency (400Hz).
- Two 115/200 V three-phase AC wild (ACW) generators are driven by each propeller reduction gearbox. These will produce a frequency range of 341 to 488 Hz.
- A transformer rectifier unit (TRU) converts ACW power to DC power for emergency use in the case of the loss of both DC generators.
- Ground power receptacles and control circuitry allow the connection of 28 V DC and 115 VAC at 400 Hz from an airfield supply or ground power unit.

In normal operation the DC generators supply power to DC BUS 1 (Right/Green) and DC BUS 2 (Left/Red). BUS 1 & 2 supply power to the utility (UTLY) BUS 1 & 2, service (SVCE) BUS, emergency (EMR) BUS, standby (STBY) BUS and essential (ESS) BUS. If one of the generators fail, the generator control unit (GCU) and BUS power control unit (BPCU) allows power to be distributed to DC BUS 1 and 2 simultaneously via a BUS tie contactor.

If both generators fail, DC Emergency Electrical network (DC EMER BUS, DC STBY BUS and DC ESS BUSES) are respectively supplied by main and emergency batteries through the HOT EMER BAT BUS and the HOT MAIN BAT BUS. In addition, providing there is ACW power available, the TRU can be selected by the pilot to supply 28 V DC power to the DC EMER BUS via a contactor designated 95PA and to the DC ESS BUS via another contactor designated as 96PA.

Change to the power distribution system operation

As a result of two previously reported temporary losses of the cockpit display units and IESI, an EASA Emergency Airworthiness Directive E-AD 2021-0120-E was released. It identified that the probable cause was likely to be the failure of battery master toggle switch, known as functional ident number (FIN) 7PA, or a failure of contactor FIN 1PA. To mitigate the risk of the ATR 42-500 post MOD 05948 ("600 version") and ATR 72-212A post MOD 05948 ("600 version"), ATR required physical testing and examination of these components and replacement if necessary. In addition, to reduce the risk further, all flights were to be carried out with the TRU selected ON from initial start-up of the aircraft to shut down on completion of the flight. The QRH was amended accordingly. This applied to EI-GPN which was being flown within the requirements of this AD. In this configuration the DC generators supply the main BUS 1 & 2 and the TRU supplies the DC EMER, ESS and STBY BUS. Figure 8 shows the DC system with the TRU in operation.

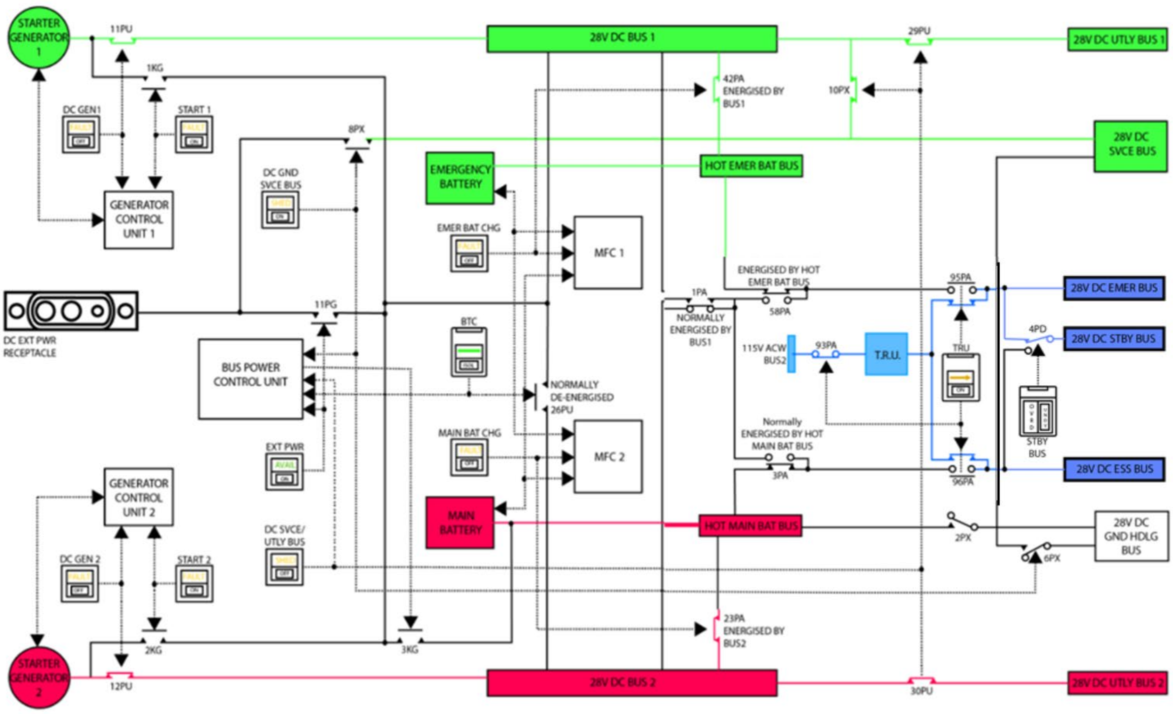

Figure 8

DC power supply configuration during the flight.

Contactor description

The application of electrical power to the various busbars is carried out by an array of remotely controlled contactors on a distribution panel on the rear right side of the cockpit. The 1PA, 95PA and 96PA contactors are the same part number, SM150D19, and have the same specifications. Figure 9 shows the array of contactors within the distribution board in the aircraft, the 95PA contactor is on the bottom right of the picture.

Figure 9
The 95PA contactor as fitted to EI-GPN

The SM150D19 contactor is a device designed to allow remote control switching in high current applications. These contactors are generally used to allow light current switches to be used on instrument and control panels, reducing the need for bulky switch gear and cabling where space is at a premium.

Contactor operation

A schematic of the SM150D19 contactor is shown in Figure 10. In the dormant or deenergised condition, a small spring holds the plunger carrying the contact plate (shown in green) against main contacts B3 and B2. The auxiliary contacts operate simultaneously with the main contact plates as the contactor is energised and de-energised. They direct voltage to illuminate status indication graphics within the electrical system cockpit control switches.

When a voltage is applied to the solenoid terminals 7 and 8, on selection of the TRU, the plunger moves against spring force and the contact plate moves away from contacts B3 and B2 breaking the circuit. As it continues moving, the lower contact plate (shown in orange) is pulled against contacts A1 and A2. At the same time, auxiliary contacts 6/2 open and 9/5 are closed[17]. Continuity between main contacts A1 and A2 remains whilst the solenoid is energised. A suppressor is fitted across terminal 7 and 8 to prevent the back EMF, generated as the plunger moves in its magnetic field, from damaging the control switch gear.

Footnote

[17] Auxiliary contact number 6 and number 2 (Contactor 95PA de-energised) provide an electrical ground to illuminate the emergency battery arrow caution in case of emergency battery discharge. Auxiliary contact number 9 and number 5 (Contactor 95PA energised, TRU engaged), provide a 28 VDC from TRU output, to illuminate the arrow of TRU switch to indicate that the TRU is engaged and operational. Contacts 1 and 4 are unused and are open circuit.

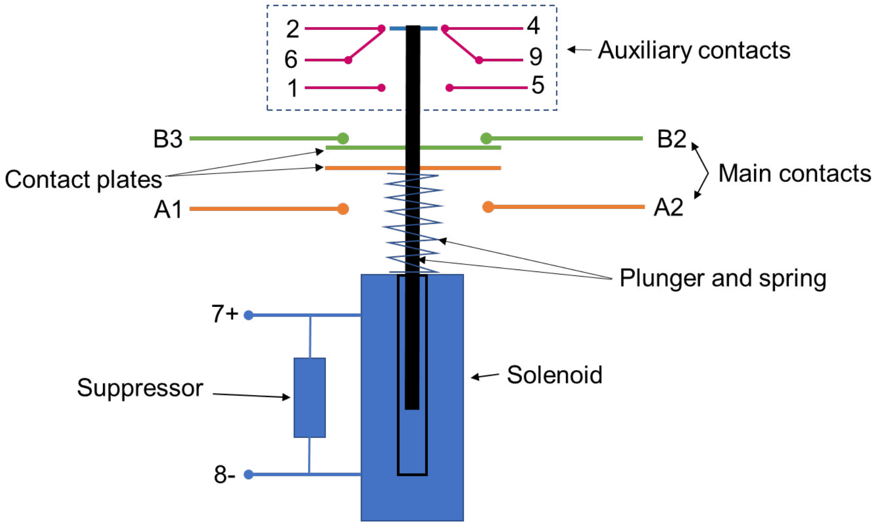

Figure 10

Contactor schematic diagram (shown de-energised)

The plunger assembly consist of two parts; the plunger and plunger pin. The plunger pin is held in a hole drilled in the plunger by a form of interference[18] fit. (Figure 11). During manufacture the minimum force required to insert the pin into the hole is 70 lbs. When correctly assembled, the force required to withdraw the pin, known as the pull-out force, is 80-100 lbs.

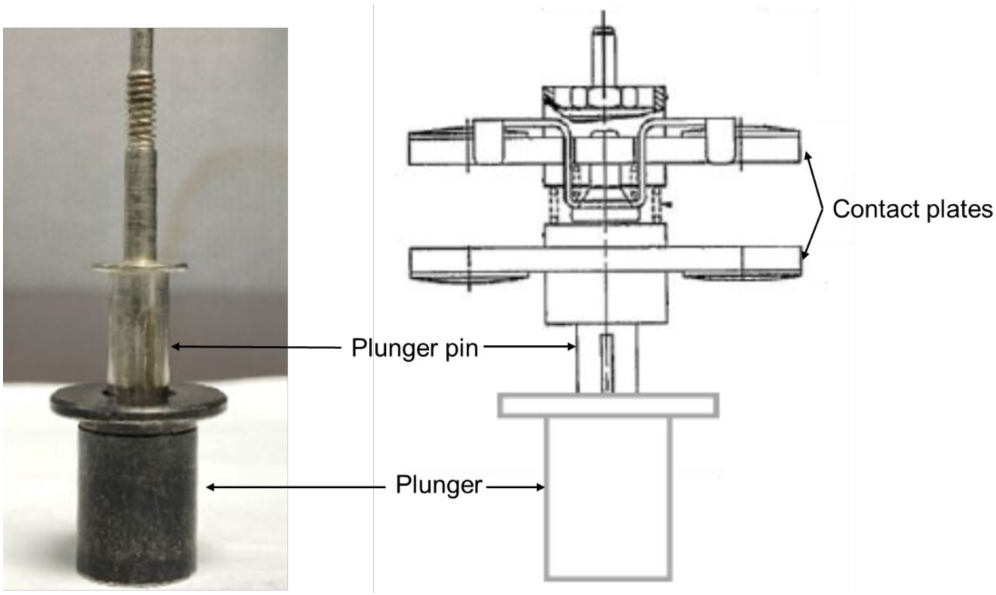

Figure 11

Plunger and pin assembly
(The plunger and pin photograph shows both components prior to insertion)

Footnote

[18] Form of interference fit – in this case the diameter of the hole in the plunger of the pin are dimensionally the same. During pin manufacture a groove is indented length wise on the surface of the pin. This has the effect of displacing material upwards on either side of the indentation slightly increasing the pin diameter in those areas. When the pin is inserted in the plunger hole this raised material creates a localised interference fit between the raised material and plunger hole surfaces.

Hydraulic systems

The aircraft is fitted with two hydraulic systems, designated as the blue and green systems. Hydraulic pressure is supplied at 3,000 psi in both systems by electrically driven pumps powered by the ACW electrical system. The blue system pump takes its power from AC BUS 1 and the green pump is powered from AC BUS 2. The blue system pump control and alerts take their power from the DC EMER BUS. The green system pump control is powered by the DC ESS BUS SECT 2 and its alerts are powered by the EMER BUS.

The blue hydraulic system powers the nosewheel steering, flaps, roll spoilers and propeller brake. It also charges the emergency brake accumulator for the parking and emergency wheel braking system.

The green system powers the landing gear and normal wheel braking.

Flying control systems

The aircraft is fitted with conventional servo tab elevator, rudder and aileron flying controls. The controls are operated via cables, pulleys and bell-cranks. Electrically driven autopilot actuators and control surface trim actuators are fitted within each of the systems.

Pitch trim system

The pitch trim system consists of two electrically driven actuators which move the servo tabs, fitted to the left and right elevators, up or down to achieve the desired trim. They are synchronised in normal operation and are able to desynchronise should one of the servo tabs malfunction. The trim actuators take 28 V DC from the EMER BUS and are controlled by double toggle switches on both control yokes. The trim actuators also receive control input demands from the automatic flight control system and automatic trim system. If the pitch trim system loses normal power supply a simple standby pitch trim guarded toggle switch may be used. The standby trim system takes its power from DC BUS SECT 2.

Landing gear control system

The green hydraulic system provides hydraulic power to retract and extend the landing gear. The system is operated by a toggle lever on the cockpit centre panel. The lever is located in up and down detents and must be pulled outwards to release it from the relevant detent. Three illuminated landing gear status indicators are located above the lever. Landing gear electrical control and primary indication and warning is supplied from the STBY BUS. Landing gear secondary indication is taken from DC BUS 2 SECT 1.

Aircraft examination

The aircraft was quarantined and examined at Belfast City Airport. Ground electrical power was applied, and the aircraft systems and displays were configured as they had been at the time of the incident. The engines and therefore generators were not running. On selection of TRU ON, numerous systems dropped off-line and DC STBY BUS and EMER BUS also indicated offline. The aircraft system status pages confirmed that this was the case. When the TRU was selected OFF, the systems returned to normal. With the aid of the aircraft circuit diagrams and the assistance of the operator's line engineer, a malfunction of the 95PA contactor was identified as the most likely cause. System functional checks carried out on the aircraft confirmed this was the case. The 95PA contactor was replaced and further testing of the systems and operation of the TRU corroborated this. The aircraft was released back to the operator and placed back into service; there has been no recurrence of the malfunction.

Contactor testing

A decal on the cylindrical solenoid casing of the contactor shows the part number, specifications and contactor internal circuit diagram. An alpha numeric code was printed on the contactor frame which read, 'MFD 1513'. This is a code which means that this contactor was manufactured during week 13 of 2015.[19]

EI-GPN was built during 2015 but it is not known if this 95PA contactor was fitted at that time. These components are not serial numbered or tracked and are not under a service life policy, the 95PA contactor may have been installed during the build process.

Preliminary visual examination and continuity testing was carried out at the AAIB with the contactor in the de-energised condition. The contactor was undamaged and in good condition. The solenoid coil resistance was found to be 50.1 ohms and therefore was within the manufacturer's specification. There was electrical continuity between terminals B2 and B3 which was correct when in the de-energised condition.

The contactor was sent to the manufacturer for a more detailed test and examination under the supervision of the National Transportation Safety Board (NTSB) Accredited Representative. A test load of 150 A was connected to the main terminals A1/A2 and B2/B3. Several energising and de-energising cycles were carried out and during a fifth cycle, the A1/A2 terminals remained open when the contactor was energised. They should have been closed when in this condition. The B2/B3 terminal worked correctly, so were closed when de-energised and open when energised. In addition, it was found that the auxiliary contacts, 1/6, 2/6, 4/9 and 5/9 operated correctly in the de-energised condition but incorrectly in the energised condition.

The contactor was disassembled and it was found that the contact surfaces on the contact plate and on the A1/A2 contacts showed evidence of arcing and poor connection. Further examination found that the pin had slipped 0.0196 inches out of the plunger hole. A pull-out test was also carried out and the pin moved with a force of 18 lbs. The minimum pull-out force should have been 80-100 lbs.

Tests and research

During this investigation five other SM150D19 contactors in use in the 95PA and 96PA circuit locations failed in other aircraft. These were examined by the OEM in conjunction

Footnote

[19] The SM150D19 manufacturer's warranty is 3 years from the date of manufacture.

with the contactor from EI-GPN. It was found that the pin had moved within the plunger in all these contactors and they exhibited a pull-out force of between 18 and 30 lbs. Three of these contactors were manufactured during 2015. The other two were manufactured in 2019 and 2020. Metallurgical and dimensional analysis was then carried out on the pins and plungers.

The material specification, hardness and plating treatments on the pin and plunger in all cases were found to be correct. Slight dimensional variations were found in the pin indentation and pin insertion depth when compared to the design specifications, but these were within tolerance.

As a control, pin and plunger pull-out and dimensional tests were carried out on sets of high cycle contactors made between 1995 and 2007. Another set of contactors made during 2023 were energised and de-energised over 50,000 mechanical (100,000 electrical) cycles over a period of nine hours at an ambient temperature of 71°C. The pull-out test carried out on the older 1995 to 2007 pins and plungers found three of them to exceed the 100 lbs force required and one with a pull-out force of 94 lb. There was no pin slippage in these assemblies. The newer 2023 set all exhibited pull-out figures of between 80 and 91 lb and there was also no pin slippage.

Example plungers taken from older and newer assemblies were sectioned and measured. This found the dimensions of some of the older pin groove indentation marks left in the bore of the plunger were less than those marks in newer plungers. Figure 12 shows the difference in the dimension with a mean of 0.0245 inches in the older plunger and a mean 0.0319 inches in the newer plunger.

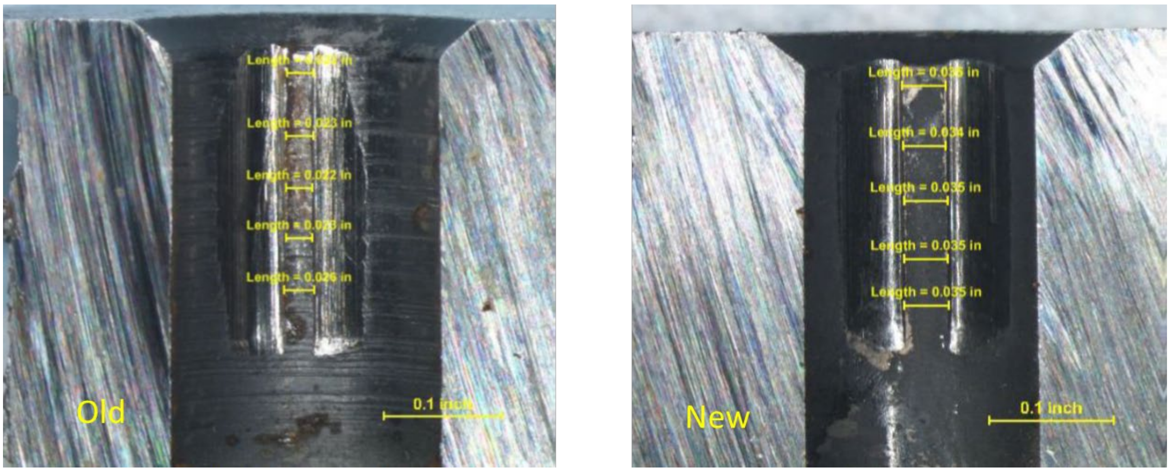

Figure 12

Plunger bore dimensions of the grooves left by the pin

Simulator session and discussions with manufacturer

Overview

The AAIB attended a simulator session at the manufacturer's headquarters on 25 November 2022 to explore the technical and procedural aspects of the event, using the incident location and flight conditions. With no function to simulate the 95PA contactor failure, the incident conditions were recreated by failing the DC SBY BUS[20] then the DC EMER BUS, and inverter 1 (Figure 13). Consequently, the manufacturer estimated the technical aspects of the simulation were accurate but that anomalies were possible.

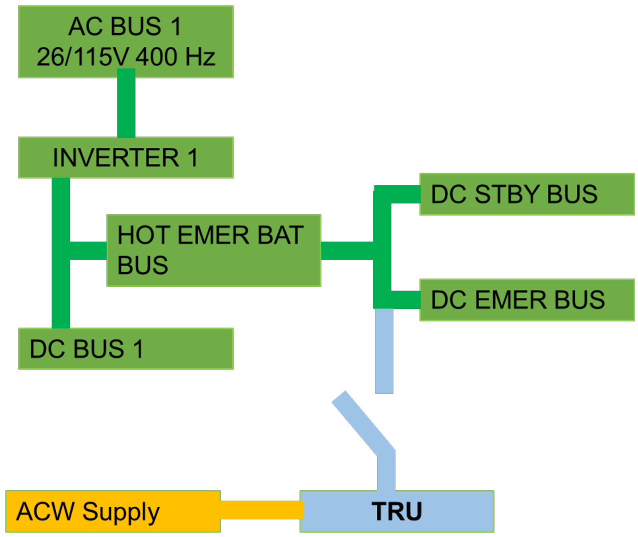

Figure 13

Simulator circuit configuration to recreate the loss of DC STBY BUS and DC EMER BUS

The simulator pilots demonstrated resolving the failure while in a holding pattern using OEB 56 Issue 3, which was published after the incident[21] (Figure 14). Accordingly, the session was not intended to assess any real startle or surprise experienced by EI-GPN's crew. The manufacturer indicated it recognised the significance of the failure for an unsuspecting crew. It said it might anticipate crew taking time to perform outstanding procedures before flying an approach, using the EWD or QRH as necessary.

Lost equipment

The *'DC EMER BUS OFF'* and *'DC STBY BUS FAILURE'* QRH procedures, and discussions with the manufacturer indicated a substantial list of lost equipment including autopilot, VHF1, multipurpose control panel[22] 1, normal pitch trim control, rudder trim, aileron trim, blue hydraulic pump, transponder 1, a navigation process module[23], and a significant number of indication lights. Some de-icing boots and all anti-icing controllers would be lost, requiring the crew to *'leave and avoid… icing conditions'*. A persisting failure would

Footnote

[20] Flight crew typically deal with alerts in the order they are presented.
[21] Publication date 30 November 2022.
[22] Used to control the virtual control panel format on MFD.
[23] Core processing module (CPM) 1.

require the *'Landing gear gravity extension'* and *'Reduced flaps landing'* procedures to be performed. Nosewheel steering and outboard anti-skid would be unavailable. However, under the circumstances of the incident, the *'DC EMER BUS OFF'* and *'DC STBY BUS FAILURE'* QRH procedures required selecting the TRU OFF.

Simulator session

The simulator session and associated discussions demonstrated standby pitch trim control would have functioned during the incident. The co-pilot's ADC switch[24] would have retrieved PFD information on his side. One flight director and one ILS display might have been available. The LANDING GEAR NOT DOWN warning occurred because one radio altimeter failed with the power levers at FLIGHT IDLE. The manufacturer suggested that, rather than all the engine instruments being "frozen", there were crosses on some of them, while others – for example, TRQ, NP and NH[25] – probably remained operational. Losing the propeller electronic control (PEC) caused the increase in NP. During the simulation, FMS 1 failed. Unlike the incident pilots' recollections, the heading bug, altitude preselect, and VSI remained unaffected, and EFCP-R functioned while EFCP-L did not.

IN FLIGHT

In case of alert:

- **ELEC DC EMER**, or
- **ELEC DC ESS**, or
- **ELEC DC SBY BUS**, or
- **ELEC STBY UNDV**, or
- **FWS not avail** and **PACK 1+2 Fault**.

Before performing the associated procedure(s):

▶ TRU.. OFF

■ **If the bus is recovered**

▶ TRU : MAINTAIN OFF UNTIL END OF THE FLIGHT, EVEN IF TRU ON IS REQUESTED IN A SUBSEQUENT PROCEDURE.

Note

Check and, if necessary, restore the equipment(s) of the recovered bus (AP, air conditioning/ pressurization, baro settings, Navaids, FMS, ...).

TRU is considered as inoperative.

Maintenance action will be required at destination.

■ **If failure persists**

▶ **LAND ASAP**

▶ TRU : MAINTAIN OFF UNTIL END OF THE FLIGHT, EVEN IF TRU ON IS REQUESTED IN THE SUBSEQUENT PROCEDURE(S).

▶ ASSOCIATED PROCEDURE(S).. APPLY

Note

Only one EFCP Procedure Control pushbuttons side is operative.

***

In case of:

- AUTO-PILOT (AP) disconnection, and

Note

AP remains available.

- TRU arrow light comes off.

Perform the following procedure:

▶ TRU.. OFF

Note

Maintenance action will be required at destination.

Figure 14

Excerpt of updated OEB 56 (Issue3)

Footnote

[24] Displays ADC information from the Captain's side.

[25] NH is displayed on the Engine SD page.

The *'Flight crew training manual'* (FCTM) for the aircraft specified *'SOP*[26] *Golden rules'*, which included *'FLY, NAVIGATE, COMMUNICATE – IN THAT ORDER'*.

Startle and surprise

The International Civil Aviation Organization's (ICAO) website included a presentation on managing startle[27]. It specified *'Cognitive effects of startle'* including *'Information processing tasks such as attention, perception, situational awareness, problem solving and decision making can be markedly impacted… Communication is often disorganised and incoherent for some time.'*

The European Union Aviation Safety Agency (EASA) published a research project on *'Startle effect management'*[28]. It stated:

> *'…in an unclear or ambiguous situation… high levels of physiological and psychological stress can persist.*
>
> *…when the fight or flight response is strong… [it] creates a sense of urgency to take action, perceived time pressure. This action-mode inhibits slow and deliberate analysis.*
>
> *The duration of the surprise response is typically longer than that of the startle reflex. The discrepancy between expected and actual circumstances requires the person experiencing the surprise to reevaluate the situation to continue with the task… people tend to focus on the most salient information, which may not be the most important information at that moment (Rivera et al, 2014).'*

An academic paper[29] on pilot stress, startle and surprise, quoted the authors of a relevant model as saying *'…stress is thought to cause a shift from analytical skills toward intuitive judgement, making one susceptible to biases'*. Plan continuation bias means continuing with the original plan despite cues indicating a different plan is preferrable. It often occurs in dynamically changing conditions.

The CAA of New Zealand's *'Situation awareness'* document stated[30] *'We have limited ability to divide attention amongst tasks and generally, have to switch attention back and forth between tasks'*.

Footnote

26 Standard Operating Procedure.
27 Microsoft PowerPoint - Managing Startle Individual Crew and Organizational Strategies Wayne Martin (icao.int) [accessed 27 July 2023].
28 R:\SM1\1.1 SAR\1.1.2 RCO\6_PROJ_EASA\Research\2015\2015.C22 Startle Effect Management STEM\3-Deliverables\Final Report\research-project-cover-page (europa.eu) [accessed 27 July 2023].
29 Frontiers | A narrative review of the interconnection between pilot acute stress, startle, and surprise effects in the aviation context: Contribution of physiological measurements (frontiersin.org) [accessed 27 July 2023].
30 Situational awareness guidance (aviation.govt.nz) [accessed 5 May 2023].

The UK CAA's *'Civil Aviation Publication 737'* (CAP 737)[31] stated the following under *'Surprise and startle'*:

'…the alarm element of the fight or flight[32] *response also appears to have an immediate and sustained impact on our cognition. Almost all mental capacity becomes focussed on the threat and/or the escape from it…* [It] *is accompanied by an urge to be engaged in the active solution… But if resources are not given to assessment and problem solving then the person cannot decide the best response. This situation would be best described as a vicious circle'.* It suggested to *'align the task expectation in a way that recognizes the cognitive response'*, with *'linear, simple, rule*[33]*-based responses'* being *'preferred in such situations… The classic rule of 'aviate, navigate, communicate' is a very good starting point in most cases…'.*

Its *'Situation awareness'* chapter suggested pilots can use a systematic process, for example, *'Rotate attention from plane to path to people (aviate, navigate, communicate)…'* any time they need to.

Some operators use models like *'plane, path, people'* to help crews maintain situation awareness and manage startle. This operator expressed keenness to maximise learning from this incident, and stated its intent to adopt a 'rule-based' structure for assisting its crews accordingly.

Analysis

Electrical system failure

The electrical system failures during the approach to Belfast City Airport was caused by a malfunction within the SM150D19 contactor designated as the 95PA contactor. Within the circuit, it supplies 28 V DC output from the TRU to the STBY and EMER BUS bars. On this occasion, whilst 95PA was in the energised condition continuity was lost between the A1 and A2 terminal contacts. This was caused by the pin carrying the contact plate slipping out of its correct position as a result of its movement within the plunger.

The results of the metallurgical and dimensional tests were inconclusive. However, the combination of tiny differences may have coalesced to allow the slippage of the pin and plunger in a batch of contactors made during 2015 and two outliers made in 2019 and 2020.

Based on the year that EI-GPN was built, 2015, and the contactor date of manufacture, it is likely this was the original item fitted at aircraft build. Until the introduction of the E-AD 2021-0120-E, ordinarily the 95PA and 96PA contactors remained in a de-energised condition other than for occasional routine testing of the TRU. However, after introduction of the AD, these contactors were now required to remain in an energised condition throughout the flight.

Footnote

[31] CAP737 Flight-crew human factors handbook (caa.co.uk) [accessed 27 July 2023].
[32] Fight or flight – physiological response to threat. Subtly different to startle reflex although they can both occur in response to the same threat.
[33] From Rasumussen's *'Skill Rule Knowledge'* model. Rule-based responses are suited to abnormal situation management because they require less conscious effort than knowledge-based ones, and can be more reliable than more instinctive skill-based responses.

There are numerous SM150D19 contactors used in this aircraft type and many of them are regularly held in the energised condition whilst in service without any problems. However, in cases where they have failed, the result has generally not been as noticeable because fewer systems have tripped off-line and have been routinely dealt with by referring to a procedure set out in the QRH. In these cases, the aircraft then continues with the flight and lands safely with the malfunctioning contactor being replaced as required and the aircraft released to service. In this case, the 95PA contactor affected quite a broad range of seemingly unrelated systems via the STBY and EMER BUS BARS and the failure of this combination was not covered by a specific procedure in the QRH. It therefore was more difficult for the pilots to troubleshoot and eventually resolve.

E-AD 2021-0120-E was developed and issued to address the potential problems with the 7PA battery master toggle switch the and FIN 1PA contactor. It is possible the in service experience of the reliability of the SM150D19 contactors, meant that the effect of the failure of the 95PA or 96PA was not considered a significant risk at the time.

It is likely the 95PA contactor on EI-GPN had a dormant anomaly, which was perhaps a less tightly assembled pin and plunger. As this was now under increased use, it started to slide out of position. It eventually reached the point where the contactor plate between terminals A1 and A2 could no longer make proper contact. The presence of arcing on the contact terminals suggests the slippage was gradual and took place over a number of cycles. The total number of cycles this contactor had carried out at the time of failure is unknown.

However, this did not affect the de-energised condition whereby the internal spring takes over and the contact plate between terminals B2 and B3 was re-established. Therefore, the DC power distribution system returns to normal with systems properly powered when the TRU was selected OFF. This is what happened when the aircraft commander deselected the TRU thereby deenergised the 95PA contactor and returning power to the affected aircraft systems.

Flight crew decision making surrounding the TRU

Having previously queried operating with the TRU ON, the commander appeared conscious of how it affected the applicability of the QRH procedure during the first flight. In those circumstances, the QRH procedure required the crew to keep the TRU ON and arrange maintenance action on arrival. With no persisting fault after arriving at Leeds, the commander – in liaison with the operator's engineering department – took the practical decision of returning the aircraft to Belfast where company engineers could inspect it.

During the incident, with the QRH checklist still in his mind, the commander selected TRU OFF, attempting to resolve the failure by returning the aircraft to what he termed its "original design" (in reference to its electrical configuration prior to OEB 56).

Effects of the failure

Significance

Some anomalies existed between the manufacturer's simulator session and the flight crews' recollection of the event – for example, EFCP and engine instrumentation functionality – but the overall significance of the failure was similar. The manufacturer and the operator recognised the challenging nature of the 95PA contactor failure, which caused unforeseen and significant problems with major systems. This included its effect on, instrumentation, primary and secondary flying controls, landing gear, autoflight, engines, communications, navigation, and operational procedure access for flight crew.

Startle and surprise

The CVR and information from the flight crew indicated supportive teamworking during the event between crew members. The sudden magnitude of the failure caused a degree of natural startle and surprise, which characteristically affected aspects of their communication and information processing. Accordingly, their experience provides opportunity to explore startle management.

The ambiguous nature, and unclear source, of the technical symptoms caused persisting stress and surprise while the flight crew attempted to re-evaluate the situation. Information from both pilots alluded to the disorientating effects of flight instrumentation and EWD abnormalities. Being apparently unable to access electronic procedures removed part of their habitual rule-based response, which could have helped them to recover from the effects of startle and surprise.

The dynamic nature of the incident perpetuated the surprise, probably raising any potential for plan continuation bias, as the crew commenced then continued with the approach while focussing on the salient features of the failure but without some systems necessary for landing. The commander had experienced electrical smoke during previous simulator sessions which possibly exacerbated a 'fight or flight' response. He described feeling time pressured and focussed on, what could be considered, the active solutions of landing the aircraft and resolving the technical failure. Continuing the approach without the landing gear and flaps deploying, the pressure on the commander continually increased. He perceived there was insufficient time to use landing gear gravity extension while also feeling concern over already difficult pitch control forces worsening during a go-around manoeuvre. Consequently, he intuitively turned off the TRU at around 1,900 ft amsl, fortunately restoring lost systems. Some plan continuation bias might have persisted while the flight crew attempted to achieve approach stabilisation, which occurred around 500 ft agl. That was somewhat below the operator's revised stabilisation height of 1,000ft but coincident with its previously specified figure.

Situation management

As part of the manufacturer's safety action, an abnormal procedure has been included in OEB 56 Issue 3, which its simulator pilots used to demonstrate resolving the incident failure. That particular procedure was unavailable to the incident crew leaving them with no clear course of action. While recognising the challenging nature of that situation, the manufacturer recommended pilots consider taking time to complete any outstanding procedures before flying an approach. Relevant QRH procedures during the incident would probably have resulted in the TRU being selected OFF. Otherwise, standby pitch trim and ADC switching were functioning, and the *'Landing gear gravity extension'* and *'Reduced flaps landing'* procedures were available. Such rule-based responses alleviating any startle and surprise. Notwithstanding any need to refer to offside instruments, giving control of the aircraft to the co-pilot could reduce the commander's physical and cognitive workload, assisting with rebuilding situation awareness for completing any briefing and decision-making processes.

EI-GPN's crew intuitively, though successfully, resolved the startling and complex failure whilst flying the approach. However, given that pressure on them had been rising as the approach continued, making time to regain situation awareness might have weakened the fight or flight response, and revealed other options ahead of reaching a stage where an intuitive response became necessary.

As well as being used to prioritise tasks, situation management tools like *'Fly, navigate and communicate'* and *'Plane, path and people'* can help crew update their situation awareness, and manage startle and surprise. Performing a simple, linear rule together can help crews structure their analysis, manage workload, lower stress, and generate options for any subsequent decision-making process. Possibly suited to EI-GPN's unforeseen failure, where certain normal cues were removed and there was no clear course of action. Such processes can preclude plan continuation bias if alternative options include delaying commencing an approach to troubleshoot a technical failure, complete checklists and configure the aircraft; or discontinuing an approach after resolving a failure to rebuild situation awareness, particularly if stability criteria cannot be met.

Wishing to proactively assist its crew during potentially challenging circumstances, the operator stated its intent to adopt a rule-based structure for situation management, helping crew to manage startle and rebuild situation awareness.

Conclusion

The aircraft was operating under EASA Emergency Airworthiness Directive E-AD 2021-0120-E which had been introduced to de-risk potential problems within the battery master toggle switch and the 1PA contactor. This meant that the TRU was selected ON and the 95PA and 96PA contactors were energised throughout all flights.

In this case the 95PA contactor failed when the TRU was selected ON and thereby not properly energising, disconnecting the DC output from the TRU to the STBY and EMER BUS bars. This caused a number of vital aircraft systems to drop off-line during the aircraft's approach to Belfast City Airport.

The extreme, unforeseen, and dynamic nature of the failure caused characteristic startle and surprise effects in the flight crew. Without a specified procedure to follow, they continued flying the approach, successfully restoring systems by turning off the TRU which restored electrical power to the affected systems by de-energising failed relay 95PA.

The effect of a malfunction of the 95PA or the 96PA contactor when the AD was issued may not have been fully understood, and so an in-flight rectification procedure had not been introduced into the QRH to allow the flight crew to identify, troubleshoot and restore systems. The report considers situation management methods for helping crew mitigate startle and rebuild situation awareness before completing an approach.

Technical cause of the contactor failure

The failure of this 95PA contactor fitted in EI-GPN was caused by a slippage between the plunger and pin assembly operating under increased cycles. The slippage resulted in poor connection, localised arcing and subsequent loss of continuity across its A1 and A2 terminals. A definitive cause of the pin and plunger slippage with the 95PA contactor fitted to EI-GPN and several other contactors manufactured during 2015, could not be fully determined.

Safety Actions

The aircraft manufacturer has been fully engaged in the investigation and has taken several safety actions. They have carried out additional research to understand the effect of the failure of the 95PA and 96PA contactors on the aircraft systems and the combination of malfunctions the pilots may experience and what action they should take in-flight. They have taken the following safety actions:

ATR have published Airworthiness Operator Messages (AOM 2021/05 issues 4 to 5) to give advice and direction to operators on the actions to be taken should non-normal TRU events occur whilst operating under AD 2021-0120-E. In particular Issue 5, which provided operators with Operations Engineering Bulletin (OEB) 56/3. This OEB made recommendations to operators on mitigating actions to be taken in the event of the temporary loss of all cockpit display systems and recommendations in case of electrical failure during the flight while the TRU is ON.

They have also addressed the technical issues that required the introduction of the AD 2021-0120-E by taking the following safety action.

An AOM 2021/05 issue 6 was issued on 7 March 2023 to publish Service Bulletins ATR42-24-0062 and ATR72-24-1032. These SB introduce a modification to the battery toggle switch (FIN 7PA) circuit integration. As per EASA AD 2023-0078R1 published on 20 April 2023, the embodiment of these SB removes the requirement to operate with TRU ON.

The operator stated its intent to maximise learning from this incident, adopting a rule-based structure to proactively assist crews with managing startle and rebuilding situation awareness.

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