

EVALUATION, INVESTIGATION TECHNIQUES AND POSSIBILITY OF MALFUNCTION OF ELECTRIC SYSTEM OF TU-154M

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Abstract

The paper discusses the electric power system of the Tu-154M. After brief introduction to aircraft power systems, the results of reverse design and analysis of $\Gamma T40\Pi\check{C}6$ wound-field synchronous generator including short circuit have been presented. An example of failure of $\Gamma T40\Pi\check{C}6$ is the fire of the Tu-154B-2 on January 1, 2011 before taking off at Surgut airport (flight 7K348). Guidelines for proper investigation of aircraft electric equipment and wiring after crash have been given. There is no evidence of examination of most electrical equipment of the Tu-154M nr 101 after crash on April 10, 2010. It is now extremely difficult to determine, if the electric system of the Tu-154M Nr 101 was operating correctly in the last seconds of flight, or not.

Keywords – aircraft electric power system, failure, investigation after crash, synchronous generator, Tu-154M.

Streszczenie

Artykuł omawia system elektroenergetyczny samolotu Tu-154M. Po krótkim wprowadzeniu do systemów elektroenergetycznych samolotów, przedstawiono wyniki projektowania odwrotnego oraz analizy generatora synchronicznego $\Gamma T40\Pi\check{C}6$ o wzbudzeniu elektromagnetycznym z uwzględnieniem przebiegów prądów podczas zwarcia. Przykładem awarii generatora $\Gamma T40\Pi\check{C}6$ jest pożar Tu-154B-2 w dniu 1 stycznia 2011 przed startem na lotnisku w Surgucie (lot 7K348). Podano wytyczne do badań wyposażenia oraz instalacji elektrycznej samolotów po katastrofie. Brak jest dowodów na przeprowadzenie prawidłowych badań większości wyposażenia elektrycznego Tu-154M nr 101 po katastrofie w dniu 10 kwietnia 2010. Obecnie jest bardzo trudno stwierdzić, czy nastąpiła awaria systemu elektroenergetycznego Tu-154M Nr 101 w ostatnich sekundach lotu, czy też nie.

Słowa kluczowe – awaria, badania po katastrofie, generator synchroniczny, system elektroenergetyczny samolotów, Tu-154M.

1. INTRODUCTION TO AIRCRAFT ELECTRIC SYSTEMS

The function of the aircraft electrical system is to generate, regulate and distribute electrical power throughout the aircraft [6,7]. Aircraft electrical components operate on many different voltages both AC and DC. Most systems use 115/200 V AC (400 Hz) and 28 V DC. There are several different electric generators on large aircraft to be able to handle loads, for redundancy, and for emergency situations, which include [6]:

- engine driven main generators;
- auxiliary power units (APU);
- ram air turbines (RAT);
- external power, i.e., ground power unit (GPU).

Each of the engines on an aircraft drives one or more a.c. generators via special transmission system.

The power produced by these generators is used in normal flight to supply the entire aircraft with power. The power generated by APUs is used while the aircraft is on the ground during maintenance and for engine starting. Most aircraft can use the APU while in flight as a backup power source. RATs are used in the case of a generator or APU failure, as an emergency power source. External power may only be used with the aircraft on the ground. A GPU (stationary or portable unit) provides a.c. power through an external plug. Aircraft generators are usually *wound-field salient-pole rotor synchronous machines* with synchronous brushless exciter and permanent magnet (PM) brushless subexciter. PM brushless generators are rather avoided due to difficulties with shutting down the power in failure modes. A generator control unit (GCU), or voltage regulator, is used to control generator output. The generator shaft is driven by a turbine engine with the aid of gears or directly by low spool engine shaft.

Typical AC power system is 115/200 V, 400 Hz, three-phase system. Since the speed of an aircraft engine varies from full power speed to flight idle speed (typically 2:1), and frequency is proportional to the generator rotational speed, a device for converting a variable speed to constant speed is necessary [7]. The so called *constant speed drive* (CSD), i.e., a complex hydromechanical device was common until the late 1980s. Nowadays, solid state converters have replaced unreliable CSDs with *variable speed/constant frequency* (VSCF) systems [7].

2. TU-154M POWER SYSTEM

The main power supply system of the Tu154M is a three-phase 115/200V, 3 x 40 kVA, 400 Hz, AC system [5,9,10]. The three-phase 115/220 V AC power is delivered by three $\Gamma T40\Pi\check{C}6$ wound-field synchronous generators. The fourth $\Gamma T40\Pi\check{C}6$ AC generator is the APU generator. The APU is also equipped with 27 V DC $\Gamma C-12TO$ starter-generator.

The secondary three-phase, 36 V, 400 Hz, 46.8-A, 2 x 3 kW AC system takes power from the main system via two three-phase 206/37 V, Dy, TC330C04B transformers. The primary windings of TC330C04B transformers are connected to the navigation piloting system (NPK) bus bars. The 115/200 V AC and 36 V AC power system are shown in Fig. 1 and described in Table 1.

The third power system is the DC 27 V, 200 A single-circuit systems (Fig. 2), which receives power from the main system via transformer and three BY-6A rectifiers and four 20HKBH-25 batteries.

The emergency 36 V AC power system (instead of RAT) consists of 20-30/36 V, 400 Hz, 250 VA two ПТС-250 transistor inverters fed from batteries. It feeds the gyro

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horizon АГР-144. Another single-phase 115-V emergency system takes electric power from batteries via ПOC-125ТЧ static converter.

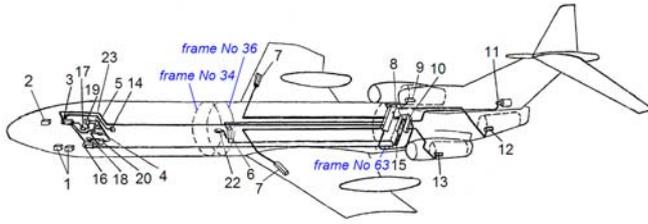


Fig. 1. Main power distribution system 115/220 V AC and 36 V AC of Tu-154M. 1 - rectifiers BY-6A (backup and No 1), 2 - rectifier BY-6A No 2, 3 - right junction box (JB) 115/200 V, 4 - converter ПТС-250 No 2, 5 – converter ПТС-250 No 1, 6 – JB of kitchen, 7 – JB of anti-ice system, 8 – right panel of generators, 9 – generator ГТ40ПЧ6 No 3, 10 – JB of APU 200 V, 11 – generator ГТ40ПЧ6 of APU, 12 – generator ГТ40ПЧ6 No 2, 13 – generator ГТ40ПЧ6 No 1, 14 – external power connector for ШРАП-400-3Φ GPU, 15 – left panel of generators, 16 – left JB 115/220 V, 17 – transformer No 2, 18 – transformer No 1, 19 – right JB 36 V AC, 20 – left JB 36 V AC, 22 - flight attendant switchboard, 23 – converter ПOC-125ТЧ [10].

Table 1. AC power systems

Voltage, V	115/220	36
Number of phases	3	3
Nominal power of the system	120 kVA	6.0 kW
Number of channels	3	2
Nominal power per channel (one generator)	40 kVA	3.0 kW
Maximum power per channel	50 kVA	3.75 kW
5-min overload power	60 kVA	4.50 kW
5-s overload power	80 kVA	6.0 kW
Frequency, Hz	400	400
Nominal current per channel, A	111	46.8
Maximum current per channel	138	58.0
Power factor	0.8 to 1.0	0.8

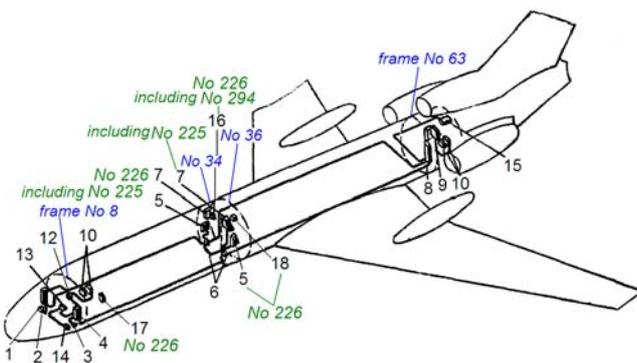


Fig. 2. Power distribution system 27 V DC of Tu-154M. 1 – Rectifier BY-6A No 2, 2 – right panel of protection control, 3 – Rectifier BY-6A No 1, 4 – Left panel of protection control, 5 – junction box (JB) of kitchen, 6 - left power JB 27 V DC, 7 – electrical panel of flight attendant, 8 – rear JB (in left panel of generators), 9 – JB of APU and batteries, 10 – batteries 20NKBN-25, 12 – JB of backup BY-6A rectifier, 14 – backup rectifier BY-6A, 15 – “PT” JB, 16 – electrical panel of household devices, 17 – electrical panel of crew cupboard, 18 – flight attendant switchboard [10].

The simplified electrical diagram of 115/200 V AC electric system is shown in Fig. 3. The block diagram of overall electric system of the Tu-154M is shown in Fig. 4.

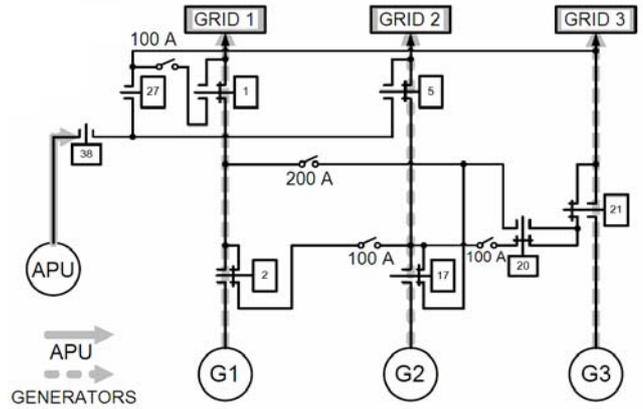


Fig. 3. Simplified schematic of main electric power system 115/220 V AC when all generators G1, G2, and G3 are in parallel. 1 – contactor ТКС133ДОД “reconnection of grid No 1 on generator No 3”, 2 – contactor ТКС233ДОД “switching generator No 1 on grid”, 5 – contactor ТКС233ДОД “switching APU on grid No 2”, 17 – contactor ТКС233ДОД “switching generator No 2 on grid”, 20 – contactor ТКС233ДОД “reconnection of grid No 3 on generator No 1”, 21 – contactor ТКС233ДОД “switching generator No 3 on grid”, 27 – contactor ТКС203ДОД “switching APU or GPU on grid No 3”, 38 – contactor ТКС203ДОД “switching APU on grid” [2].

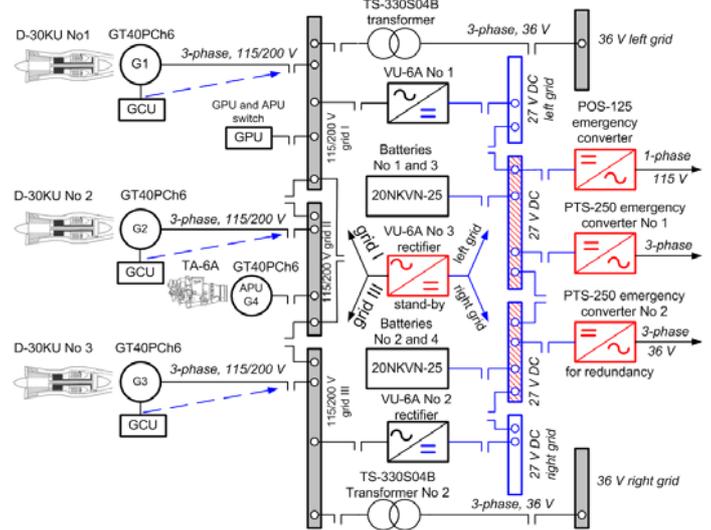


Fig.4. Block diagram of electric power system of Tu-154M [9].

3. ELECTRIC POWER DISTRIBUTION

The main three-phase, 115/200 V, 400 Hz power supply system is a three-channel system (Figs 3 and 4). One ГТ40ПЧ6 generator feeds one channel (electric grid). The generator No 1 mounted on the left turbofan engine feeds the grid No 1, which in turn feeds the radio navigation equipment, aircraft control system, fuel pumps, passenger cabins lighting, pumping station of the second hydraulic system and other loads. The generator No 2 of the second grid mounted on the center engine feeds anti-ice heating elements of leading edges of wings (slats). The third grid powered by the generator No 3 installed on the right engine is loaded with fuel pumps, fuel control system, air conditioning system, pumping station of the third hydraulic system, household equipment and other equipment. In the

case of failure of one of the generators, its grid it automatically reconnected to the operating generators.

The GPU supplies all three electric grids. After starting any turbofan engine and after switching on any ГТ40ПЧ6 generator, the first and the third grid is automatically connected to this generator while the GPU feeds only the second grid. If two generators are on, the GPU is automatically disconnected from the aircraft electric power system.

Control and protection devices of the main power system are located on the power panel of the flight engineer.

The three-phase 36-V, 400-Hz, two-channel electric power system feeds the Купс-МП-2 navigation and control unit, АРК-15 radio compass, Гроза-154 radar, ДИСС-ЗП instrument, hydraulic pressure gauge and the first sub-channel МЭТ-4Б. The 36 V AC also supplies the attitude indicator, but its power is supplied independently of the ПТС-250 converter, which receives electrical energy from batteries. The ПТС-250 No 1 converter is used as an emergency 36 V AC power source (Fig. 4). Connection of the converter to the network is made automatically.

The on-board 27 V DC power system consists of three ВУ-6А rectifiers, ГС-12ТО starter-generator mounted on the APU, and two four 20НКВН-25 batteries (Fig. 4). The ВУ-6А rectifiers are the basic DC power sources. They get the power from the first and third grid (from the main 115/200 V AC system). There are two basic rectifiers and the third rectifier is for redundancy. The third rectifier is switched on automatically in the case of failure of one of the basic rectifiers and operates in parallel with the remaining rectifiers. There is also provision for "forced" connection of the third reserve rectifier.

The 27 V DC ГС-12ТО starter-generator delivers power to the DC grid after starting the APU on the ground until turbofan engines are started and ГТ40ПЧ6 synchronous generators operate. In the case of failure of the main 115/200 V power system in the air, rechargeable batteries are used to supply the most important loads and to start the APU on the ground in the absence of GPU. Under normal operation, batteries are connected in parallel to smooth the DC bus voltage ripple. Rechargeable batteries are installed in the rear fuselage under the floor of the technical compartment. They can be accessed through a removable hatch in the floor.

In addition, there is a 27 V AC power supply designed for household appliances: electric kettles and electric warmer in the kitchenette-buffet. The system gets its power from the main system through a ТС-330С04А transformer connected to the grid via a switch mounted on the flight attendant switchboard (Figs 1 and 2). The transformer is installed on the right board, near the frame No 35, in junction box (JB) of the kitchen (Fig. 2.)

The single-phase 115 V AC, 400 Hz power supply provides electric power to Ландыш-20 FM radio station, РСБН-2СА system, Купс-МП-2 navigation and control unit, and other radio equipment, as well 2ИА-7А temperature meters of engine exhaust gases. In the case of emergency, the electrical power to these loads comes from the converter МА-100М, which is supplied from batteries. The connection of inverter is made automatically.

The cross section of basic distribution wires is:

- 1.93 to 35.0 mm² for AC systems
- 1.5 to 70.0 mm² for DC systems

4. SYNCHRONOUS GENERATORS

The main generators are three 40-kVA, 115/200 V, 400 Hz, 6000 rpm, CSD ГТ40ПЧ6 wound-field synchronous generators driven by three Д-30КУ turbofan engines (Fig. 5). Each generator feeds one channel. There is also a reserve 40-kVA, 115/200 V, 400 Hz APU, which consists of ГТ40ПЧ6 synchronous generator driven by independent ТА-6А turbine engine (Fig. 6).

The construction and principle of operation of the generator ГТ40ПЧ6 that is installed on the APU, is similar to generators installed on the turbofan engines Д-30КУ.

The longitudinal section of ГТ40ПЧ6 synchronous generator is shown in Fig. 7. From better packaging point of view, the PM brushless subexciter is placed inside the exciter.

The ГТ40ПЧ6 generator operates smoothly under the following conditions:

- ambient temperature from +100 to – 60° C;
- cooling air temperature from +60 to – 60°С;
- atmospheric pressure up to 124 mm Hg;
- effects of frost and dew;
- shock accelerations up to 6g.

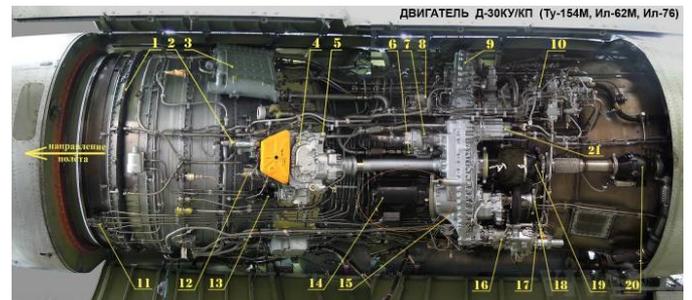


Fig. 5. Turbofan engine Д-30КУ. 1 – inlet guide vanes heating collector (BHA), 2 – centrifugal air separator of oil system, 3 – fuel-oil heat exchanger, 4 – main oil pump, 5 – front (main) accessory drive gearbox, 6 – hydraulic pump for thrust reverse, 7 – fuel pump, 8 – sensor of referred revolutions, 9 - place for aircraft hydraulic pumps НН-25 and НН-89, 10 – fuel pump regulator, 11 – temperature sensor, 12 – centrifugal regulator of low pressure (LP) rotor, 13 – rotational speed sensor for the LP rotor, 14 – synchronous generator ГТ40ПЧ6, 15 – rear accessory drive gearbox, 16 – constant speed drive (CSD), 17 – mechanism of frequency correction, 18 – air turbine of CSD, 19 – air turbo starter, 20 – overlapping cover of turbo starter, 21 – oil removal pump. <http://ru.wikipedia.org/>

The housing monoblock is made of magnesium alloy with pressed steel sleeve mounted on the drive side around the ball bearing. The bearing nest has a pocket for the collection of waste grease that is removed from it with the aid of a plunger. Lubricant is applied to the bearing on the oil line through the point of lubrication.

There are longitudinal ribs on the inner surface of the housing, which increase its rigidity and form channels for passage of cooling air. Openings in the enclosure at the drive side are designed to exit the air. Titanium flange screwed to the end shield mounts the generator on the engine (Fig. 7). A box on the outer surface of the housing contains a differential current transformer for protection of the generator.

The rotor has two ball bearings. Seals of the bearings are threaded type with extra cuffs. The rotor salient poles, armature of the exciter and PMs of subexciter are pressed on

the hollow shaft. The rotating passive rectifier consists of six silicon diodes Д232А.

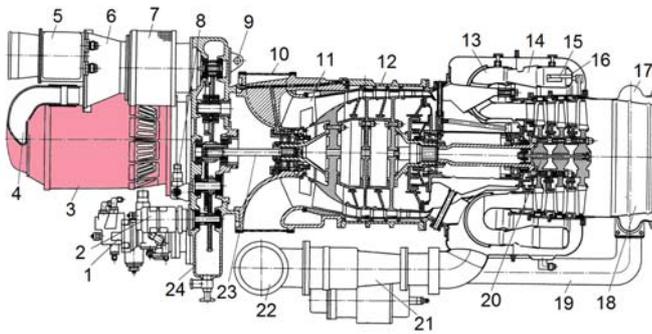


Fig. 6. APU with ГТ40ПЧ6 synchronous generator and TA-6A turboshaft engine. 1 – fuel pump-regulator, 2 – sensor of tachogenerator, 3 – synchronous generator ГТ40ПЧ6, 4 – leads of synchronous generator, 5 – air-oil heat exchanger, 6 – adapter, 7 – fan, 8 – stabilizer of oil pressure, 9 – front suspension rigging, 10 – grid of compressor, 11 – radial-circular entrance, 12 – compressor, 13 – gas collector, 14 – combustion chamber, 15 – evaporation tube, 16 – head of flame tube, 17 – snail, 18 – exhaust pipe, 19 – air bypass pipeline, 20 – turbine, 21 – air regulator, 22 – bleed air pipe, 23 – spring, 24 – reducer [5].

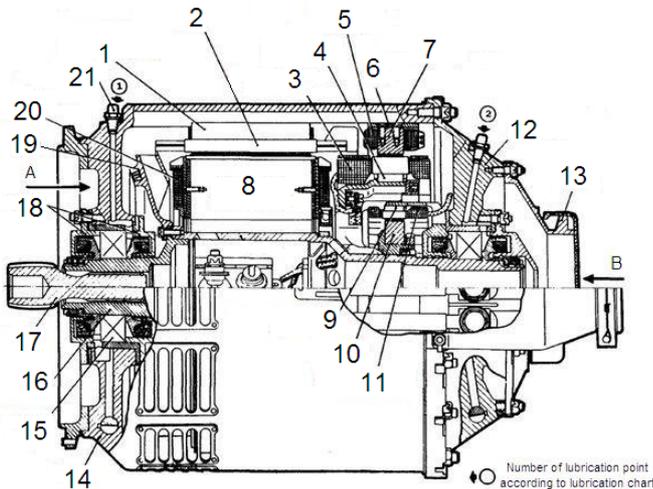


Fig. 7. Wound-field air-cooled synchronous generator ГТ40ПЧ6: 1 – armature core of main generator, 2 – armature winding of main generator, 3 – armature winding of exciter, 4 – armature core of exciter, 5 – field winding of exciter, 6 – pole, 7 – field excitation system of exciter, 8 – rotor pole of main generator, 9 – armature of subexciter, 10 – PM, 11 – armature winding of subexciter, 12 – end shield, 13 – nozzle, 14 – housing, 15 – bearing, 16 – hollow shaft of rotor, 17 – shaft end, 18 – flanges, 19 – fan, 20 – field winding of main generator, 21 – point of lubrication.
<http://s010.radikal.ru/i314/1010/42/cba147b70185.jpg>

Cooling of the generator is accomplished by blowing air at a flow rate varying from 0.1 to 0.3 kg/s.

Dimensions, material data and winding diagrams of the ГТ40ПЧ6 synchronous generator are not available. To obtain dimensions, winding parameters and detailed performance characteristics of ГТ40ПЧ6 synchronous generators a reverse design on the basis of available sources [3,5,9,10] has been done. Table 2 shows selected stator (armature) and rotor parameters. The finite element method (FEM) has been used to obtain the 2D magnetic flux distribution in the cross section of the main generator.

Table 2. Parameters of ГТ40ПЧ6 synchronous generator

Stator	
Number of phases	3
Stator phase voltage, V rms	115
Nominal armature current, A	111
Armature winding resistance per phase at 25°C, Ω	0.0264
Base impedance, Ω	0.9919
<i>d</i> -axis synchronous reactance, p.u.	1.954
<i>q</i> -axis synchronous reactance, p.u.	0.776
Rotor	
Type of rotor	salient pole
Pole arc-to-pole pitch ratio	0.58
Number of poles	8
DC field current at nominal load and PF=0.75, A	45.6
Total moment of inertia, kgm ²	approx. 0.06

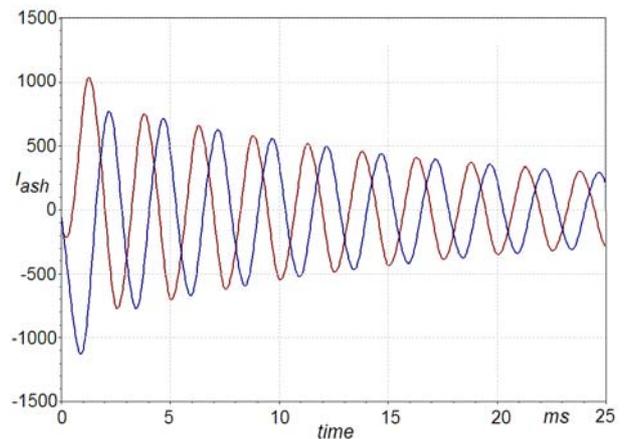


Fig. 8. Armature current I_{ash} at two lines-to-neutral short circuit of ГТ40ПЧ6 synchronous generator. The peak short-circuit current is $I_{ashp} = -1130$ A corresponds to $t = 0.6$ ms.

The FEM calculated short-circuit current waveforms are very important since the subtransient and transient short-circuit currents help to evaluate the possible damage during the electrical power system failure.

Short-circuit currents of the ГТ40ПЧ6 synchronous generator can exceed more than 11 times the nominal (rated) current $I_a = 111$ A. The most dangerous are line-to-neutral and two lines-to-neutral short circuits. Fig 8 shows the armature current $I_{ash} = f(t)$ waveforms for two lines-to-neutral short circuits, as obtained from the 2D FEM.

5. FAILURES OF SYNCHRONOUS GENERATORS

The mean time between failures MTBF of ГТ40ПЧ6 synchronous generators is estimated as approximately 8500 to 9000 flight hours and mean time between unscheduled removals (MTBUR) is estimated as approximately 5500 to 5800 flight hours [5,9,10].

There is known at least one case of main generator failure, i.e., the Tu-154B-2 RA-85588 while operating flight 7K 348 on January 1, 2011 from Surgut (located on the Ob River near the junction with Irtys River) to Moscow (Domodedovo). The plane was taxiing to the runway while preparing for its takeoff from Surgut when the right engine caught fire on the taxiway (Fig. 9). Three out of 126 passengers and 8 crew members died.

Russia's Interstate Aviation Committee (IAC) released their final report (in Russian) concluding the probable cause of the accident was the outbreak of fire in the right generator panel located between frames 62 and 64 in the cabin [2].



Fig. 9. Tail part of Tu-154B-2 RA-85588 after fire at Surgut airport on January 1, 2011 [2].

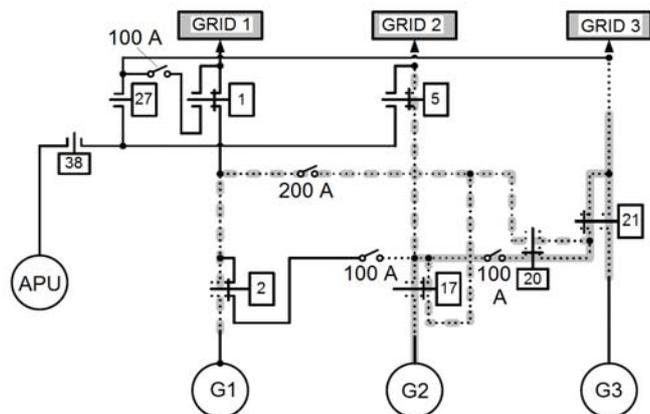


Fig. 10. Closed electric circuit on assumption of abnormal scenario corresponding to 21st contactor TKC233Д0Д “switching generator No 3 on grid” [2].

The cause of the fire was an electrical arcing produced by electrical currents exceeding 10 to 12 times the nominal current when two generators not synchronized with each other were brought online but got connected together instead of being connected to parallel busses. The unsynchronized operation of the generators can be attributed to:

- (a) Poor technical conditions of contacts TKC233Д0Д responsible for connecting the generators with the electrical busses, that were damaged by prolonged operation without maintenance. A contact normally open was welded and fractured insulation material moved between contacts that are normally closed. These abnormal contact positions led to the connection between No 2 and No 3 generators (Fig. 10).
- (b) Differences in the schematic diagrams of generator No 2 and generators No 1 and 3. When the switch is moved from "check" to "enable" with no delay in the "neutral" position, the generator 2 is brought online without time delay. This leads to increased wear of normally closed contacts in the TKC233Д0Д unit. The specific design of the electrical systems ensures power supply to each bus from either the APU or engine integrated drive generator.

The abnormal paralleling of two unsynchronized ГТ40ПЧ6-2С generators causes serious consequences. The generators were connected on the network after the engine start and exit to the idle mode. Under such conditions the currents can reach more than 10 times the nominal current of the generator (Fig 8).

6. FAILURES OF OTHER ELECTRICAL EQUIPMENT

On September 7, 2010, the Tu-154M RA-85684 Alrosa Mirny Air Enterprise Flight 514 aircraft from Udachny (located 1370 km northwest of Yakutsk on the Markha River) to Moscow suffered a complete electrical failure *en route*, leading to a loss of navigational systems. The electrically operated fuel transfer pumps were also affected and prevented transfer of the fuel from wing tanks to the engine supply tank in the fuselage.



Fig. 11. Emergency landing of Tu-154M RA-85684 at abandoned air strip near town of Izhma on September 7, 2010. The impact was damped by the young trees which have grown since the airport was closed. The photograph shows the right wing that cut a pine tree. <http://englishrussia.com/2011/11/04/the-lucky-tu-154/#more-74596>

After emergency decent below cloud level the crew were able to spot an abandoned air strip near town of Izhma (Fig. 11). The abandoned air strip is 1325 m long, whereas Tu-154 requires a minimum of 2200 m. The aircraft landed at a speed of 350 to 380 km/h, faster than normal, due to the lack of flaps. Although the flaps are powered by hydraulics, the switches operating them are electrical. All nine crew and 72 passengers evacuated using the aircraft's evacuation slides. No injuries were reported.

On November 17, 1990, the cargo TU 154M, CCCP-85664 of Aeroflot Airways was heading through Czech territory with a load of Winston cigarettes from Basel to Moscow. A switched-on cooker in the kitchenette caused a fire on board of the plane and the crew decided to land at the closest possible place. The crew made an attempt of emergency landing on the field near Dubenec village in the East Bohemia. There were only 6 crew members on board, all of them survived the air disaster.

On February 18, 1978, the Tu-154A, CCCP-85087 of Aeroflot Airways was standing on the apron at Tolmachevo Airport, Novosibirsk. The cabin heater was left working unattended between flights. A rag caught fire, which incinerated the cabin. A fire that broke out in the passenger cabin engulfed the rear part of the airframe. The forward fuselage burnt out. There were no fatalities.

7. INVESTIGATION OF ELECTRICAL EQUIPMENT AND WIRING AFTER CRASH

Electrical events happen at the speed of light. Aircraft crash at much lower speed and a lot can happen to electrical system between the first collision with ground or terrain

obstacle and complete stop. The state of electrical circuit can change in this very short time interval: circuits which were “on” at initial impact are “off” when the wreckage finally comes to stop. Finding the evidence of short circuit or electric arc does not mean that the electrical malfunction has occurred before the accident. It could rather happened during impact.

Before inspection of the wreckage it is recommended to do a homework [1,11], i.e.,

- interviewing witnesses (crew members, passenger, outsiders),
- familiarizing with air-to-ground communication, flight data recorder (FDR) and cockpit voice recorder (CVR) data, if available.

Evidence in the recordings or statements that some electrical parts and systems were operating correctly prior to impact is more credible that examination of the wreckage and saves investigators a lot of work [1,11]. If witnesses and recordings are not available, the recommended approach to investigation of the wreckage is to prove that the electrical power was available on the front end and that electrical devices were operating on the rear end of the aircraft.

7.1. Electric generators

Stator winding resistances of generators should be measured for possible open or short circuits. Also, the resistance between winding terminals and housing should be measured for possible damage to insulation. After external examination and testing, the generator should be taken apart to check for any evidence of scratching on the inside surface of the stator core, bearing failure and insulation overheating. Scoring and scratching on the stator core indicate if the generator was spinning or not before the crash [1,11].

7.2. Generator feeders

Terminals of busses should be tested for tightness, evidence of arcing and erosion of terminal studs, corrosion and foreign objects being in contact with the terminals [1].

7.3. Emergency power supply

Emergency power supply includes batteries, APU and RAT (not installed on Tu-154). If one of the main generators fails, there is usually the possibility to connect the inoperative circuit to an operative one [1,11].

7.4. Electric loads

Electrical loads include various electric motors and actuators, lights, de-icing, anti-icing, kitchen equipment, navigation instruments, flight instruments, communication equipment, radar and electronics. Similar to generators, the evidence of scrolling, scoring and scratching on the inside of the stator core indicates if the electric motor was spinning or not before the impact. Damage to electronic equipment is difficult to determine whether it was done before or after the impact [1,11].

7.5. Light bulbs analysis

Analysis of light bulbs in the cockpit can tell which lights were on or off at impact. When a tungsten filament burns, it leaves a grayish powder, i.e., the tungsten oxide. When the remaining parts of the bulb are coated with grayish powder, the bulb was probably on at the time the glass envelope broke. When the glass envelope was broken and no grayish powder was produced, any evidence of changing the color of filament (from yellow to red to purple to blue) shows that

the bulb was probably on. If the color of filament remains unchanged, the bulb was probably off. Broken glass envelope and intact filament indicates that the bulb was definitely off [1,11].

Table 3. Examination of electrical equipment at crash site

Electric equipment	Standard procedure [1,11]	Evidence of examination by IAC (MAK) and/or CINAC (KBWL) [3]
Electric generators and motors	1) Visual inspection 2) Measurements: winding resistance, insulation resistance 3) Machine taken apart: are there any scores and scratches on the inner surface of the stator core, is the shaft bent, what is the condition of bearings?	1) Probably 2) No evidence 3) No evidence
Circuit breakers, switches and relays	Inspection if contacts are free of metal flow and excessive cratering caused by arcing	No evidence
Feeders and buses	Testing for tightness, evidence of arcing and erosion of terminal studs, evidence of foreign objects.	No evidence
Light bulbs	Examination of glass envelope, filament and evidence of powder inside the glass envelope.	Some incandescent light bulbs, e.g., illumination bulbs (filaments) of IIV of radio compass APK-15M were examined by IAC (MAK) [3,4]
Electrical wiring	Visual inspection of conductor and insulation.	Probably

7.6. Circuit breakers

Circuit breakers protect the wiring, not equipment. Most circuit breakers are thermally activated. Arcing in the line not always open the circuit breaker. However, circuit breakers may open under impact forces [1,11].

7.7. Electrical wiring

Typical aircraft have from 16 to 160 km of wire installed such that wire from one system is often collocated with wire from many other systems. Electrical wiring can be classified into power wiring (heavy current) and light current wiring. In modern aircraft, power wires, feeding e.g., electric motors, are not routed through the cockpit. Switches in the cockpit are connected to light current wires (control wires), which active relies of heavy current circuit [1,11].

After crash, wiring is normally scattered throughout the wreckage, but major wire bundles remain more or less intact.

Wiring is inspected visually. The condition of wires and their insulation is a good indicator of the source of overheating. External overheating discolor or burn the insulation, while the wire strands should be intact and shiny. Internal or severe external overheating discolor the wire strands.

Older aircraft design allows circuits from multiple systems to be co-bundled along shared raceways in the fuselage. This is cost-effective solution, but deterioration of insulation, overheating or arcing of one circuit can also damage to neighboring wires. For example, short circuit in a wire bundle was a root cause of ignition of the flammable

fuel/air mixture in the center wing fuel tank (CWT) of Boeing 747-131 (flight TWA 800) on July 17, 1996.

8. EXAMINATION OF ELECTRICAL EQUIPMENT OF TU-154M ON CRASH CTE

Operation of electrical equipment and installation of the Tu-154M is monitored by the MCP11-12 flight data catastrophic recorder with the aid of parameters described in Table 4. Those parameters are plotted in Fig. 12 (color lines at the bottom).

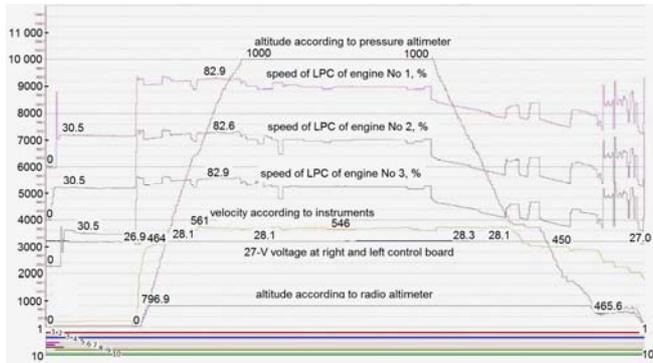


Fig. 12. Parameters of flight of Tu-154M Nr 101 for electrical equipment and installation on April 10, 2010, 7:14– 8:41 am. LPC = low pressure compressor. Description in Table 4 [4].

The catastrophic recorder MJ11-14-5 (part of MCP11) was found on April 10, 2010 by Russians. Data of MLP-14-5 were recorded in the IAC (MAK) headquarters in the presence of Polish military prosecutor on April 11, 2012 [4]. The recording medium (tape) was in good condition [4].

Annexure 4 [4] to the Report [3], Section 7.2 "Analysis of electrical installations" concludes that during the flight on April 10, 2010, the electric system operated correctly, i.e.,

- The main generators ГТ40ПЧ6 were connected to the grid immediately after starting the engines in the following sequence: engine No 2 – generator No 2, engine No. 1 – generator No 1 and engine No 3 – generator No. 3 During the flight, there were no signs of automatic or manual disconnection of any of the generators from the grid, which means that the electric system was operated in accordance with the technical guidelines.
- There were no signs of change of power supply configuration of the left and right NPK (navigation piloting system) buses. NPK buses were fed in accordance with the technical guidelines.
- There were no signs of starting the APU.
- There were no signs of the 36-V power system malfunction and no signs of automatic or manual activation of the emergency power sources for this system.
- There were no signs of the 27-V DC power system malfunction. The voltage on the left bus was within the limits in accordance with technical guidelines and there was no signal of voltage decay on the left bus.

According to latest research of K. Nowaczyk of the University of Maryland¹, the ATM quick access recorder (QAR) has recorded a damage to the left engine No 1 and synchronous generator No 1. Both the 115/200 V and 36 V

(LSIEC36) of the left grid dropped to zero before the ground impact (Table 4).

Table 4. Parameters of electrical equipment plotted in Fig. 12

No	Polish acronym	Description
1	TABLEAZS27V	27 V is on the left board AZS (automat of grid security)
2	STARTWSU	Engine starter is switched-on
3	SZYNAWA36	36 V is on the right bus of IITC-250 No 1 DC to AC converter
4	NPKP1SIEC3	NPK (navigation piloting system) bus is switched from the right grid No3 to the left grid No1
5	G1NIESPR	Generator No1 is disconnected from the grid
6	G2NIESPR	Generator No2 is disconnected from the grid
7	G3NIESPR	Generator No3 is disconnected from the grid
8	SIECPR36V	36 V is on the right bus
9	NPKL1SIEC3	NPK bus is switched from the left grid No1 to the right grid No3
10	LSIEC36V	Emergency voltage 36 V is on the left bus of IITC-250 No 2 DC to AC converter



Fig. 13. Junction and control boxes of electrical installation. Photo taken at the site of wreckage storage [4].



Fig. 14. Generator ГТ40ПЧ6 on Nr 1 (left) Д-30КУ turboprop engine. Photo taken between 11 and 13 April 2010 on the crash site [4].

There is no evidence that other than visual inspection of electrical equipment and wiring (Table 3) has been done on the crash site [3,4]. The following statement is given on p. 20/28 of Annexure 4 [10]: *Bundles of electrical wires torn apart. Control boxes deformed. Enclosures of on-board batteries deformed. Some cells leaking.* The report shows photographs of wire bundles, control boxes (Fig. 13), synchronous generator ГТ40ПЧ6 on the turboprop engine Nr 1 (Fig. 14), batteries and other electrical equipment.

¹ presented at the Smolensk Conference, Warsaw, October 22, 2012.



Fig. 15. Electromagnetic brake TЭM-4 for flap control found several meters behind the famous birch tree. Source: <http://www.waronline.org>

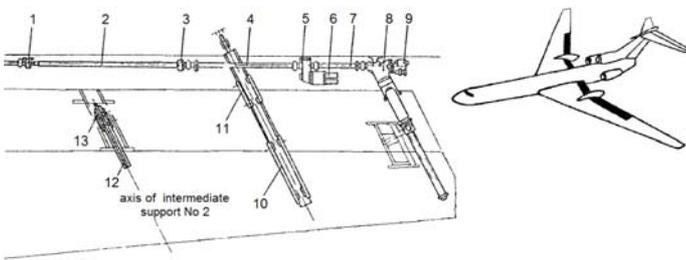


Fig. 16. Location of electromagnetic brake TЭM-4 for flap control. 1,3 - bracket, 2,4 - transmission shaft, 5 - reducer, 6 - electromagnetic brake TЭM-4, 7 - cardan joint, 8 - lift for the outer flap, 9 - mechanism of limit switches with sensor, 10 - rail of external deflector, 11 - carriage of external deflector, 12 - rail of deflector, 13 - intermediate carriage of deflector [9,10].

The object found at the crash site several meters behind the famous "armored" birch tree [3] and shown in Fig. 15 has been often incorrectly identified as a fuel pump. However, this is the electromagnetic brake TЭM4 used for control of flaps (Fig. 16).

9. CONCLUSIONS

The electric system of the Tu-154M aircraft is an outdated system typical for aircraft being designed in the 1960s. Main generators are air cooled generators. Air cooling reduces the rated power and increases the mass of generators. Nowadays, modern VSCF wound-field synchronous generators with rated power up to 250 kVA are oil cooled [7].

Reversed design and analysis of ГТ40ПЧ6 main synchronous generators deliver important information on steady-state and transient performance of these machines. Transient characteristics, especially short-circuit waveforms are very helpful in investigation of electric power system after crash.

Credibility of flight parameters for electrical equipment and installation (Fig. 12) is questionable. There is not enough information how the recorded parameters have been extracted and analyzed [4]. It is now very difficult to find out if the electric power system was operating correctly in the last seconds of crash or not. According to [3,4], the flight management system (FMS) lost electric power (memory freezing) at 10:41:05, i.e., at the time of collision with ground. Table 3 show standard procedure for examination of electrical equipment and installation after crash [1,11]. The electrical equipment and wiring at the crash site was only inspected visually [3,4]. There is still possible to examine synchronous generators and induction motors for fuel pumps and for other on-board equipment, e.g., air conditioning system. However, the results of examination may not be credible since the wreckage was carelessly loaded on the trailers, and then transported, unloaded and stored in open space without any caution.

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