Electric Power System of Tu-154M Passenger Aircraft

Abstract. The paper discusses the electric power system of the Tu-154M aircraft. After brief introduction to aircraft power systems, the results of reverse design and analysis of the GT40PCh6 wound-field synchronous generator including short circuit have been presented. Electric power distribution and assignment of electric grids (channels) to respective aircraft energy consumers has been discussed. Most important electric loads, i.e., the fuel system with electric motor driven pumps, wing anti-ice electric system and exterior and interior lighting equipment have been described. An example of failure of GT40PCh6 synchronous generator is the fire of the Tu-154B-2 on January 1, 2011 before taking off at Surgut airport (flight 7K348).

Keywords: aircraft electric power system, distribution system, electric loads, electric motor-driven fuel pumps, fuel system, lighting, synchronous generator, Tu-154M, wing anti-ice electric system

Introduction to aircraft electric systems

The function of the aircraft electrical system is to generate, regulate and distribute electrical power throughout the aircraft [4, 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 (Fig. 1) to be able to handle loads, for redundancy, and for emergency situations, which include [4, 7, 8]:

1. engine driven main generators;
2. auxiliary power unit (APU);
3. ram air turbine (RAT);
4. external power, i.e., ground power unit (GPU).

Each of the engines on an aircraft drives one or more a.c. generators (Fig. 2) via special transmission system. The electricity 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 (portable or stationary unit) provides AC power through an external plug. Aircraft generators are typically three-phase, salient-pole, wound-field synchronous generators with outer stator with distributed-parameter winding and inner rotor with concentrated coil winding [4]. The field excitation current is provided to the rotor with the aid of a brushless exciter system consisting of two synchronous machines, i.e., wound-field synchronous exciter and permanent magnet (PM) subexciter. The power circuit is shown in Fig. 2. PM brushless generators are rather avoided due to difficulties with shutting down the power in failure modes. There are also attempts of using switched reluctance (SR) generators with no windings or PMs on the rotor. 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 of aircraft 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.

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 PRZEGŁAD ELEKTROTECHNICZNY, ISSN 0033-2097, R. 89 NR 2a/2013 300
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 activate relays of heavy current circuits.

### Electric power supply system of Tu-154M

The main power supply system of the Tu154M is a three-phase 115/200V, 3 × 40 kVA, 400 Hz, AC system [3, 10, 13]. The three-phase 115/200 V AC power is delivered by the GT40PC6 wound-field synchronous generators. The fourth GT40PC6 AC generator is the APU generator. The APU is also equipped with 27 V DC GS-12TO starter-generator.

The secondary three-phase, 36 V, 400 Hz, 46.8-A, 2 × 3 kW AC system takes power from the main system via two three-phase 206/37 V, Dy, TS330S04B transformers. The primary windings of TS330S04B transformers are fed from the navigation piloting system (NPK) bus bars. The 115/200 V AC and 36 V AC power systems are shown in Fig. 3 and described in Table 1. The third grid No 3 powered by the generator No 3 in Fig. 5. The simplified schematic of main electric power generation system 115/220 V AC when all generators G1, G2, and G3 are in parallel. 1 – contactor TKS233DOD “reconnection of grid No 1 on generator No 3”; 2 – contactor TKS233DOD “switching generator No 1 on grid”; 5 – contactor TKS233DOD “switching APU on grid No 2”, 17 – contactor TKS233DOD “reconnection of grid No 3 on generator No 1”, 21 – contactor TKS233DOD “switching generator No 3 on grid”, 27 – contactor TKS233DOD “switching APU on grid No 3”, 38 – contactor TKS233DOD “switching APU on grid” [2].

### Electric power distribution

The main three-phase, 115/200 V, 400 Hz power supply system is a three-channel system (Figs 3, 5 and 6). One GT40PC6 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 left autonomous bus bars, left bus bar of navigation piloting system (NPK), radio navigation equipment, anticollision flashing lights SMI-2KM, control systems of slats and stabilizers (motors No 1), fuel pumps No 1,3,5,8,10, rectifiers VU-6A No 1,3. Passenger cabins lighting, heaters of windshields of cockpit, hydraulic pumping station NS-46 of the second hydraulic system, and other loads. The total power consumption of the grid No 1 is 23.2 kVA, 70 A (excluding NS-46).

The generator No 2 of the grid No 2 mounted on the center engine feeds the anti-ice electric heating elements of leading edges of wings (slats). The power consumption is 43.6 kVA, 130 A.

The third grid No 3 powered by the generator No 3 installed on the right engine No 3 is loaded with the right autonomous bus bars, right bus bar of navigation piloting system (NPK), control system of slats and stabilizers (motors
No 2), fuel pumps No 2.4.6.7.9.11, fuel control system, rectifiers VU-6B No 2 (No 3), air conditioning system, hydraulic pumping station NS-46 of the third hydraulic system, household equipment and other equipment. The total power consumption is 12 kVA, 45 A (without household equipment and NS-46). The household equipment needs 13 kVA, 60 A.

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

The GPU supplies all three electric grids. After starting any turbofan engine and after switching on any GT40PCh6 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 Kurs-MP-2 landing navigation and control unit, ARK-15M radio compass, Groza-154 radar, Doppler effect velocity and drift angle measure system DISS-3P, and hydraulic pressure gauge MET-4B. The 36 V AC system also supplies the gyro horizon (attitude indicator), but its power is supplied independently of the PTS-250 converter, which receives electrical energy from batteries. The PTS-250 No 1 converter is used as an emergency 36 V AC power source (Fig. 6). Connection of the converter to the network is made automatically.

Synchronous generators
The main generators are three 40-kVA, 115/200 V, 400 Hz, CSD GT40PCh6 wound-field synchronous generators driven by three D-30KU low-bypass turbofan engines (Fig. 7). Each generator feeds one channel (grid). There is also a reserve 40-kVA, 115/200 V, 400 Hz power source, the so called APU which consists of GT40PCh6 synchronous generator driven by independent TA-6A turbine engine (Fig. 8).

http://s010.radikal.ru/i314/1010/42/cba147b70185.jpg


Fig. 10. Magnetic flux distribution in the cross section of GT40PCh6 synchronous generator as obtained from the 2D FEM.

Fig. 11. Open circuit characteristics at synchronous speed $n_s = \text{const}$ obtained from analytical calculations and 2D FEM.

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. Windows 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. 9). 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 D232A.

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 GT40PCh6 synchronous generator are not available [3, 13, 10]. To obtain dimensions, winding parameters and detailed performance characteristics of the GT40PCh6 synchronous generator (Table 2), a reverse design on the basis of available sources [3, 10, 13] has been done. The 2D FEM has been used for electromagnetic analysis and synthesis. The 2D magnetic flux distribution in the cross section of the main generator as obtained from the FEM is shown in Fig. 10.

The open circuit characteristics [3] at synchronous speed $n_s = \frac{f}{p} = \text{const}$ obtained from analytical calculations and 2D FEM are shown in Fig. 11.

Short-circuit currents can exceed more than 11 times the nominal current. Figs 12 to 15 shows the armature current $I_{ash} = f(t)$ waveforms for three-phase, line-to-line, line-to-neutral and two lines-to-neutral short circuits of the GT40PCh6 synchronous generator. The most dangerous are line-to-neutral (Fig. 14) and two lines-to-neutral (Fig. 15) short circuits. The obtained 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.

Fuel supply system

Civil transport aircraft use the wing structure as an integral fuel tank to store fuel. In larger aircraft, the fuel is also stored in the structural wing box within the fuselage. A typical wing tank is irregular, long and shallow [7]. The fuel is in direct contact with the outside skin. The Tu-154M has six fuel tanks: one central fuel tank (CWT) No 1, two inner wing tanks No 2, two outer wing tanks No 3 and one additional tank No 4. The Tu-154M fuel tank configuration is shown in Figs 16
Fig. 12. Armature current $I_{ash}$ at three-phase short circuit of GT40PCh6 synchronous generator. The peak current is 911.2 A at 0.9 ms.

Fig. 13. Armature current $I_{ash}$ at line-to-line short circuit of GT40PCh6 synchronous generator. The peak current is 944.6 A at 0.95 ms.

The tanks No 3 are between spars 1 and 3 and ribs 14 and 45 of detachable parts of wings [12].

The CWT tank is generally categorized as hazardous due to the proximity to external heat sources, e.g., air conditioning units [7]. It requires tank inerting with the aid of nitrogen-enriched air from the on-board inert gas generating system. The tanks No 1 and 4 of the Tu-154M are inerted in the case of emergency landing without landing gears. The left and right wing tanks are usually categorized as nonhazardous as there is mostly no proximity of heat sources [7].

The wing leading edge slat section is equipped with anti-ice control system, typically with hot air ducts. These ducts take form of pipes with holes to allow air to heat the inner surface of leading edges. The hot air flow to the outer wing leading edges is controlled by the wing anti-ice valve [7]. The Tu-154M has electric anti-ice control system with heating elements embedded in slats.

The fuel system of the Tu-154M uses electric motor driven centrifugal pumps ECN-319, ECN-323 and ECN-325. Fuel pumps ECN-323 and ECN-325 are driven by 115/220-V AC induction motors (Fig. 18) and fuel pumps ECN-319 are driven by DC 27-V brush motors (Table 3). A flange mounted motor and pump constitute one integral unit (Fig. 19a). The feeding cables in fuel tanks are in aluminum tubes (Fig. 19b). Wiring system that delivers electric energy to fuel pump motors must be protected against electrical arcing and accumulation of static electricity that under some circumstances can cause ignition of the fuel-air mixture in the wing tank [6, 7, 9].

In general, there are two types of fuel pumps on typical aircraft [7]:

- Fuel transfer pumps (e.g., ECN-323), which perform the task of transferring fuel between the aircraft fuel tanks to ensure that the engine fuel feed requirement is satisfied;
- Fuel booster pumps (e.g., ECN-319, ECN-325) also called engine feed pumps, which are used to boost the fuel flow from the aircraft fuel system to the engine.

| Table 2. Parameters of GT40PCh6 synchronous generator |
|---------------------------------|-----------------|
| **Stator**                      |                 |
| Number of phases                | 3               |
| Connection                      | Wye             |
| Rated speed, rpm                | 6000            |
| Rated frequency, Hz             | 400             |
| Stator phase voltage, V         | 115             |
| Stator rated current, A         | 111             |
| Armature winding resistance per phase at 25°C | 0.0264 |
| Base impedance, Ω               | 0.9919          |
| d-axis synchronous reactance, p.u. | 1.954  |
| q-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 | 45.58 |
| Total moment of inertia, kgm²   | approx. 0.06    |

Fig. 14. Armature current $I_{ash}$ at line-to-neutral short circuit of GT40PCh6 synchronous generator. The peak current is 1108.2 A at 0.95 ms.

Fig. 15. Armature current $I_{ash}$ at two lines-to-neutral short circuit of GT40PCh6 synchronous generator. The peak current is 1130 A at 0.6 ms.
Fig. 16. Tu-154M fuel tank configuration: No 1 – center wing tank (CWT), i.e., collector tank, No 2 – inner left and right wing tank, No 3 – outer left and right wing tank, No 4 – additional tank [12].

Table 3. Fuel pumps of Tu-154M.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>ECN-319</th>
<th>ECN-323</th>
<th>ECN-325</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of pump</td>
<td>Emergency booster</td>
<td>Transfer</td>
<td>Booster</td>
</tr>
<tr>
<td>Number of pumps</td>
<td>2</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Electric motor</td>
<td>DC brush</td>
<td>Induction (cage)</td>
<td>Induction (cage)</td>
</tr>
<tr>
<td>Voltage, V</td>
<td>27</td>
<td>115/200</td>
<td>115/200</td>
</tr>
<tr>
<td>Rated current A</td>
<td>&lt; 15</td>
<td>&lt; 2.6</td>
<td>&lt; 8.3</td>
</tr>
<tr>
<td>Starting current</td>
<td>unknown</td>
<td>&lt; 15.6</td>
<td>49.8</td>
</tr>
<tr>
<td>Pressure drop, kG/cm²</td>
<td>1.6</td>
<td>0.45</td>
<td>1.25</td>
</tr>
<tr>
<td>Flow, l/h</td>
<td>1,500</td>
<td>2,000</td>
<td>3,500</td>
</tr>
<tr>
<td>...</td>
<td>7,000</td>
<td>...</td>
<td>12,000</td>
</tr>
<tr>
<td>Mass of pump, kg</td>
<td>3.8</td>
<td>4.0</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Commercial aircraft use open vent system to connect the ullage¹ in each tank to the outside air [7]. The Tu-154M is equipped with the vent system.

The Tu-154 uses fuel Jet A-1. Jet A-1 is a kerosene grade of fuel suitable for most aircraft turbine engines. It is produced to a stringent internationally agreed standard.

Wing anti-ice system

Most civil aircraft use hot bleed air for anti-ice control of outer wing leading edges [7]. The Tu-154M must use electric resistive heating for anti-ice of the wing leading edge slats, as the turbofan engines are tail mounted and located far away from the wings. This would make the hot air bleed system very heavy and cumbersome.

The Tu-154M has three-phase, 115-V electrical wing anti-ice heating system (Fig. 20) [3, 9, 14]. To save electrical energy, heating elements are fed cyclically by adequate determination of time period. Under cyclic heating a thin layer of ice accumulates on slats which does not deteriorate aerodynamic properties of the aircraft. When the accumulation reaches a thickness threshold and the temperature of skin increases, the ice is taken out by the air stream.

The generator GT40PC6 No 2 driven by the mid turbofan engine (Fig. 5) feeds only the electric grid 2 dedicated to heating wing slats. The electric apparent power is 43.6 kVA at 115 V (phase voltage) and < 1.30 A.

Heating elements (composites) of one half of slats are divided into eight sections. The other half of slats has also eight sections. Section are fed in the following sequence:

1st, 2nd, ... 8th, 1st, 2nd, ... 8th ...

Sections are numbered starting from the core part of the wing to the end of the wing. The current is on for 38.5 s and off for 269.5 s for each section.

In the leading part a thermal “knife” is installed along the slats. This part is made of 20-mm wide X20H80 NiCr foil. The thermal “knife” is not fed cyclically – it is steadily under current and is isolated from the outer skin by three layers of glass fiber 3 (Fig. 20). Also, the three layers 5 isolate the thermal “knife” from the heating element. On the inner skin/sheathing of heating element of the slat, thermal switches for cyclic operation of sections and thermal “knife” are installed. Thermal switches protect slats and heating elements against overheating.

Lighting

The lighting equipment of the Tu-154M is divided into external and internal equipment. External equipment is intended for taxiing, takeoff, landing, and indicate the plane in the air space at night. Interior equipment is used for illumination of the cockpit, passenger cabin and other chambers of aircraft, and emergency lighting.

The external lighting equipment includes wing navigation (position) lights BANO-57 with 70-W SM-28-70 lamps, 115 V SM-2KM anticollision flashing lights (45 flares/min), and 27 V, 35.5 A PRF-4 landing/taxi lights.

The cockpit is equipped with a general illumination systems and lamps for lighting control boards, panel of flight en-

¹ Space between the fuel surface and upper wall of the tank.
Failures of electric power system

Failures of synchronous generators

The mean time between failures (MTBF) of GT40PCh6 synchronous generators is estimated as approximately 8000 to 8500 flight hours [2, 3, 13, 16].

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 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. 21). Three out of 126 passengers and 8 crew members died.

Russia’s Interstate Aviation Committee (MAK) 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]. The generators were connected on the network after the engine start and exit to the idle mode. 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 (Fig. 22). The unsynchronized operation of the generators can be attributed to:

1. Poor technical conditions of contacts TKS233DOD (Fig. 22) 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 abnor-
mal contact positions led to the connection between No 2 and No 3 generators (Fig. 22).
2. 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 on line without time delay. This leads to increased wear of normally closed contacts in the TKS233DOD unit. The specific design of the electrical systems ensures power supply to each bus from either the APU or engine integrated drive generator.

Failures of other electrical equipment

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

After emergency decent below cloud level the crew were able to spot an abandoned air strip near town of Izhma (Fig. 23). The abandoned air strip is 1325 m, whereas the 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. The impact was damped by the young trees, which have grown since the airport was closed. All nine crew members 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 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.

Conclusions

The electric system of the Tu-154M aircraft is an outdated system typical for aircraft being designed in the 1960s. There are three GT40PCn6 wound-field synchronous generators driven by D-30KU low-bypass turbofan engines and one GT40PCn6 generator driven by the TA-6A APU turboshaft engine. The APU is also equipped with the 27 V DC GS-12TO starter generator. The Tu-154M is not equipped with a RAT.

Main synchronous generators GT40PCn6 are air cooled generators. Air cooling reduces the rated power and increases the mass of generators. Nowadays, modern VSCF wound-field synchronous generators are oil cooled with rated power up to 250 kVA (Boeing 787 Dreamliner).

Reversed design and analysis of GT40PCn6 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 malfunction, failure or crash.

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