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METHODS FOR IMPROVING THE REALIABILITY OF FUEL SUPPLY SYSTEM OF GAS TURBINE ENGINES WITH USING ELECTRICALLY DRIVEN PUMPS

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Abstract

This work presents the results of research works aiming at reliable operation of fuel supply systems with electrically-driven pumps designed for gas turbine engines (GTE). Versions of the integral fuel supply system architecture and fail-safe operation of its components are studied. Measured data for the fuel supply system with electrically-driven pumps tested in the engine demonstrator are shown.

1 Introduction

In the conventional GTE's fuel supply systems (FSS) rotation of the pumps is provided by an accessory gear box. Failures in the FSS are classified as catastrophic and its components shall meet high-level requirements for in-flight mean time to failure, because damage of any pump usually leads to an engine shutdown.

The electrically-driven pumps used in the FSS of an "electric" gas turbine engine (EGTE) - the engine for an "electric" aircraft - offer a number of benefits associated with the ability to control the pump capacity to fit the needs of the engine in all modes of operation. Using the electric drive in the fuel system entails an option to use a fuel metering method for control the parameters of engine operation process, in which the fuel flow rate depends on the pump rotational speed (a metering-free system). In this case there are also changes in the fuel supply system: there is no need in bypass and throttling valves to adjust fuel flow at the pump outlet depending on engine needs because there is no direct relation between rotational speeds of the engine and the pump.

However, use of controllable electric drives containing an electric motor and a control unit increase the probability of additional failures. This work presents methods to ensure reliability and error compensation (failure management) in electrically-driven FSS.

In case of a single fault in the EGTE's FSS, it is necessary to support the engine operation without changes in the operation mode. In case of two faults, safe switchover of GTE operation while keeping its operability is permissible.

These requirements can be met by designing the FSS with interchangeable pumps, an improvement the electric drive reliability, choice a specific type and characteristics of the pumps.

2 Fuel supply system with interchangeable pumps

For example, Fig. 1 shows a diagram of a fail-safe two-stage FSS with interchangeable electrically driven pumps. The system includes a low-pressure centrifugal pump (LPP) with an electric drive (ED-L), a high-pressure gear pump (HPP) with an electric drive (ED-H), a startup/bypass line, a fuel distributor (FD), check valves (CV1 and CV2), and other components. LPP and HPP characteristics are very close in values of max. flow. An electronic digital controller of the GTE (EDC-GTE) is used to control the electric drives.

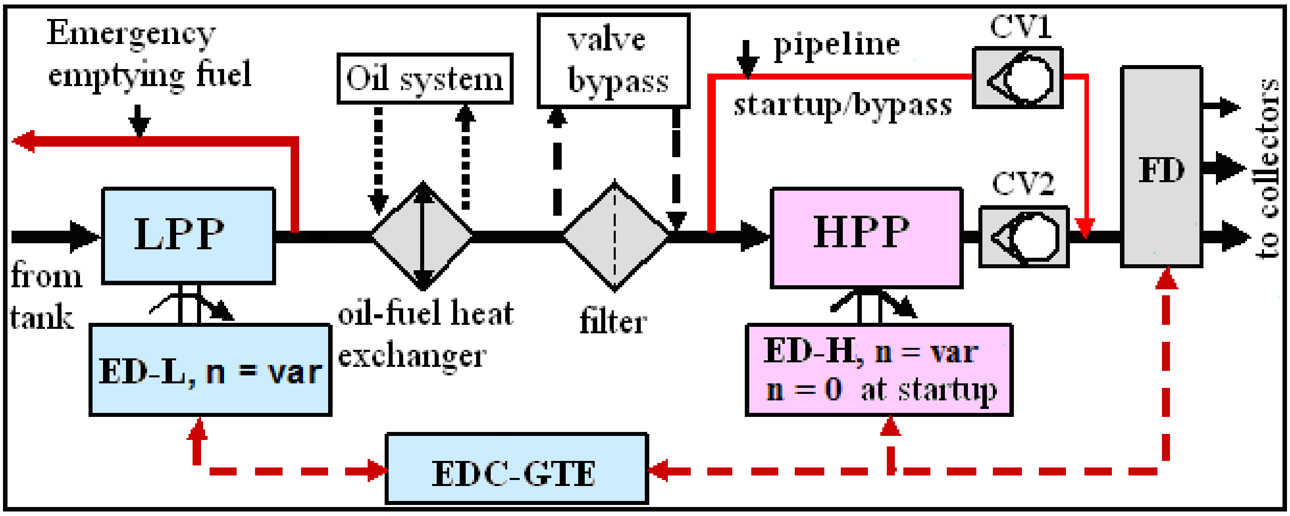

Fig. 1 Structural diagram of a fail-safe FSS for GTE

Only ED-L is in operation in engine startup conditions (Fuel is supplied to the engine injectors via a startup line to provide HPP bypass. When the CV1 valve is in automatic opening, CV2 is closing. In idling (SG) conditions the ED-H is actuated, CV2 is open and CV1 is closed. Both pumps supply fuel to the engine by commands from the EDC-GTE controller.

In normal FSS operation the EDC-GTE controller specifies the required engine fuel flow and depending on its value a HPP Speed signal is generated. This signal (setpoint) is sent to the HPP ED-H electric drive and provides the required fuel flow. Simultaneously, EDC-GTE generates a signal of required current in EP-L windings to provide pressure as sufficient for normal HPP operation without cavitation.

If the high-pressure pump is failed, the EDC-GTE generates a signal to cut off the ED-H electric drive and switch over to the LPP ED-L electric drive to support its rotational speed as required for fuel supply to the combustion chamber.

If the low-pressure pump is failed, the high-pressure pump provides fuel flow. To prevent HPP cavitations, the EDC-GTE controller decreases engine rotational speed making possible to continue the aircraft flight and perform landing.

3 Algorithmic redundant electric drive control

To rotate the GTE system pumps, valve electric drives with permanent rotor magnets are used. They contain an electric motor and a control unit operating in control mode of the ED speed, n_{ed}, or current in its windings, I_{ed}, i.e. torque of the ED shaft. The torque value is proportional to the differential pressure in the pump. Fig. 2 shows the control system electric diagram for the ED pump.

When operating at constant ED shaft speed, actual speed, n_{ed}(U2), signals from an integrated speed sensor and rotational speed setpoint, $n_{ed\ ref}$ (U1), signals from the GTE control system are sent to the speed controller inlet. When operating at constant torque, the current controller installed in the electric motor shaft is in operation. Signals of actual current from the current sensor and the current setpoint from the EDC-GTE are transmitted to the current controller inlet. Maximum current value is limited.

Rotor position sensors and current regulators (Ua and Tb, respectively) send signals to the inlet of the switch operating in relay mode with switching frequency >10 kHz. The switch operation is in pulse-duration modulation mode and its control signals provide required sequence and ON time of windings.

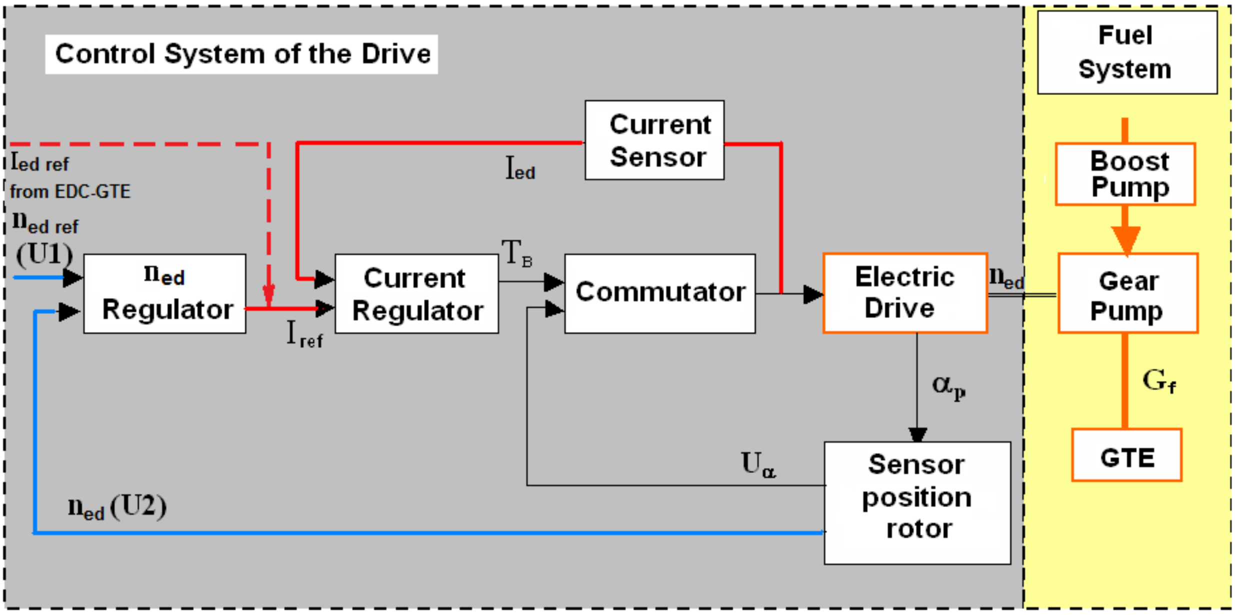

Fig. 2 Drive control system schematic

GTE operation is possible with motor speed control or current control. Fuel consumption with speed control is linearly dependent on control signals, and with current control – the differential pressure of the pump varies linearly, ΔP_p (difference between outlet (Pout) and inlet (Pin) pressure) [1]. The experimental characteristics of the fuel supply system as dependencies of fuel flow (Qf) or pressure difference in the pump (Pout - Pin) versus current control signal, $I_{ed\ ref}$, for operation in an engine demonstrator engine and in a semi-scale simulation test rig are shown in Fig. 3.

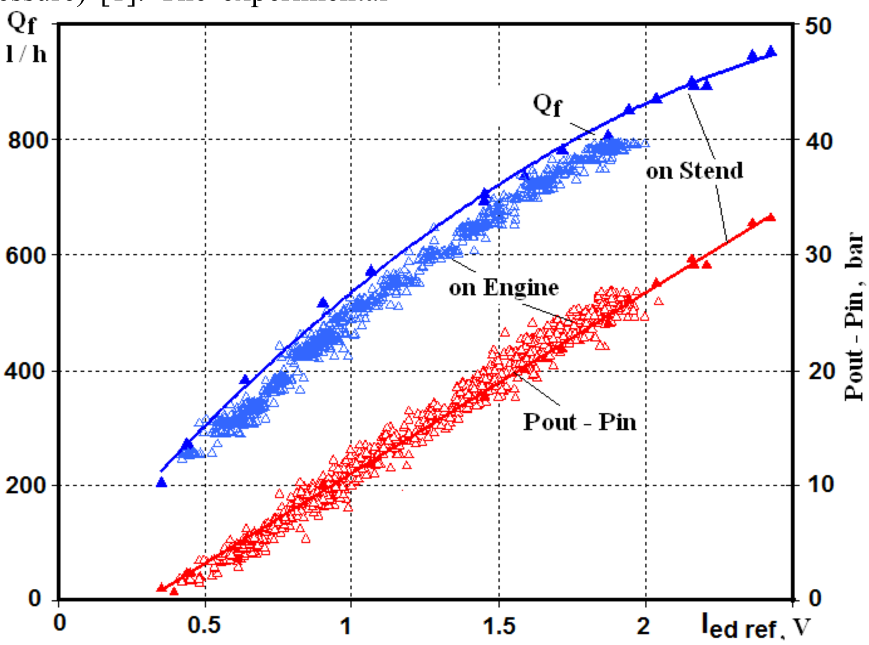

Fig.3 Static characteristics of the fuel supply system

Dynamic characteristics of the fuel supply system with the motor speed control, n_{ed}, or with current control in the windings, I_{ed}, are considerably different in transient process time. Fig. 4 shows pressure variations at the HPP outlet as a function of sudden changes in the control signal, setting fuel flow from 20% to 100% for different control systems.

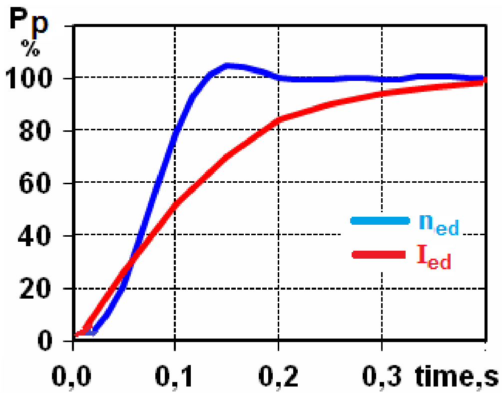

Fig. 4 Transients pressure at the pump outlet for different ED control methods

Transition time with speed control is 0.2 sec that is twice less than with current control.

Transient processes in the GTE with current control of the fuel pump electric drive are shown in Fig. 5. In case of a sudden change in the I_{ed} control signal for switching over from Q_f = 245 l/h to Q_f = 350 l/h, fuel flow increases in the transient process up to 400 l/hr due to a delay in pressure rise in the combustion chamber (P_2). Changes in rotational speed n_2, and pressure P_2, in the high-pressure compressor (HPC) are smooth and without overshooting

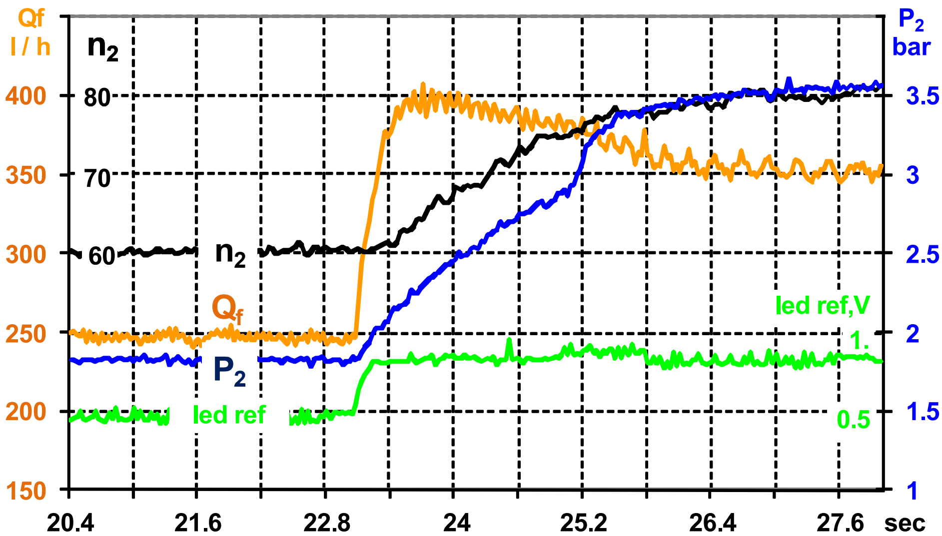

Fig. 5 Transient processes in the GTE with the GP electric drive controlled by current

This feature of transient processes is associated with the electric drive control by current, when pressure difference instead of fuel flow is supported in the pump. Pressure at the pump outlet depends on the electric drive response time, and pressure at the compressor outlet depends on HPC rotor response time (i.e. considerably higher), consequently, there is a delay in pressure variations at the HPC outlet as compared with pressure variations at the pump outlet.

Excessive fuel supply to the combustion chamber is not observed with ED speed control. Due to this fact, speed control is a preferable option. Current control can be proposed as a backup control, e.g. in case of the speed sensor failure. The electrically driven pump is designed for fuel supply and fuel flow control by changing speed of the valve electric drive.

4 Reliability of electrically driven pump components

Methods aiming at reliability of electrically-driven pumps for error compensation (failure management) in mechanics of the pump drive (damage of the shaft connecting the electric motor and the pump, shaft jamming), mechanical damages in the pumps (destruction of the shaft bearings, damage in the pump flow path, etc.) as well as failure of the electric drive (the electric motor or its control unit). If there is any failure, the pump takes a position of an additional throttle in the fuel supply line. In this case the pump rotor can be non-rotating (shaft jamming, throttle mode), or continue its rotation in windmilling mode.

Experimental studies of the DCN-44S centrifugal boost pump performances in windmilling and pump jamming conditions show that there is an increase in pressure losses in the pump from 0.15 to 0.4 MPa with an increase in fuel flow from 100 to 3500 l/hr (Fig. 6). Pressure loss in windmilling conditions is lower by 25 ... 30%.

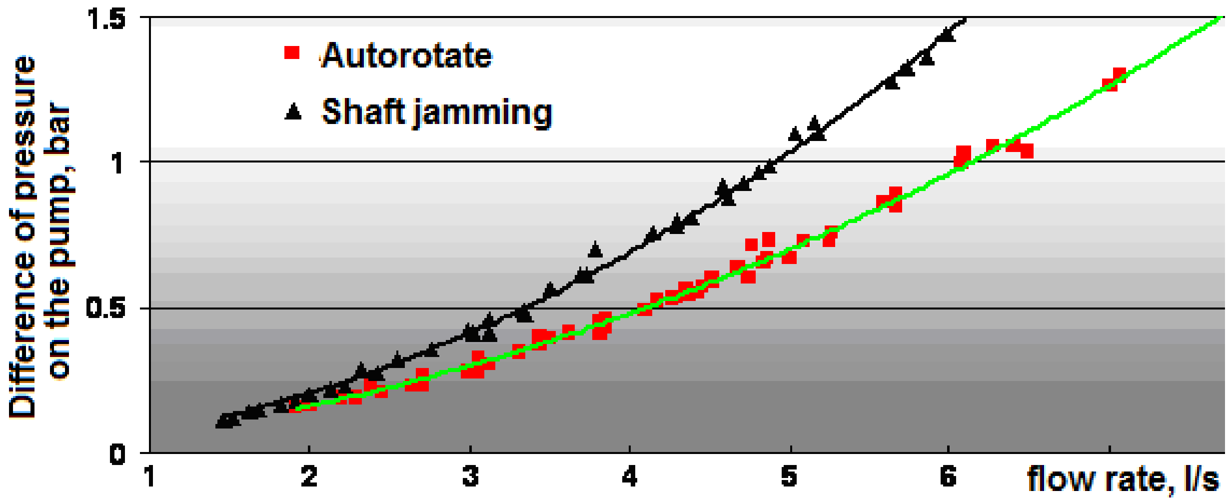

Fig.6 Pressure losses in the centrifugal pump flow path

Analysis of the experimental data shows that drag coefficient of the flow path in the decelerated centrifugal pump is close to the drag coefficient at the squared flow in the equation approximating its pumping pressure characteristic by a second order polynomial.

Considering the fact that pressure losses in the centrifugal pump are also observed in windmilling conditions, in case of failure in the pump drive system it is necessary to switch over to decreased flow (twice decrease in fuel flow can decrease pressure difference by four times) while disconnecting the pump electric drive.

For an electrically driven gear pump with the flow path used as a throttling valve, simple electric drive OFF is not sufficient; it is necessary to provide a fuel bypass valve actuating in failure events. This is an automatic process in the fuel supply system shown in Fig. 1 - when the CV2 valve is closing, the CV1 valve is opening.

Windmilling parameters depend on friction forces arising in sealing cups between the pump flow path and the "dry" motor with air cooling. Sealing cups are pressed against the shaft under action of pressure at the pump inlet generating a static friction force exceeding the dynamic friction force. The friction effect is mostly noticeable in startups of these electrically driven pumps, when the "static friction forces" are maximal. Fig. 7 shows the transient processes in the fuel supply system, when the gear pump drive is actuated by the U1 control signal at 1.0sec**.**

It is clear that there is a delay in rotor rotation startup (Fig. 1) – there is no fuel flow (Q_f) in the fuel supply system even in case of U1 control signal transmission. The electric motor starts rotation only after 12 seconds and changes in the system parameters.

To test this effect, pressure value at the pump inlet (Pin) decreases from 2.5 bar to 1.4 bar. The rotor starts rotation at a lower control signal value (0.7 V instead of 1.1 V).

For "wet" motors, where rotor and stator are cooled by fuel, there is no the sealing cup between the pump and the electric motor, and the rotation delay effect is eliminated, that improves the operation reliability. Fuel pumping through the electric motor provides heat takeoff from its bearings with an increase in their lifetime.

Weight of the "wet" electric drive with the fuel cooled rotor and stator is by 40 - 50% lower than without cooling due to possibility to use the current overload capacity of the valve electric motor.

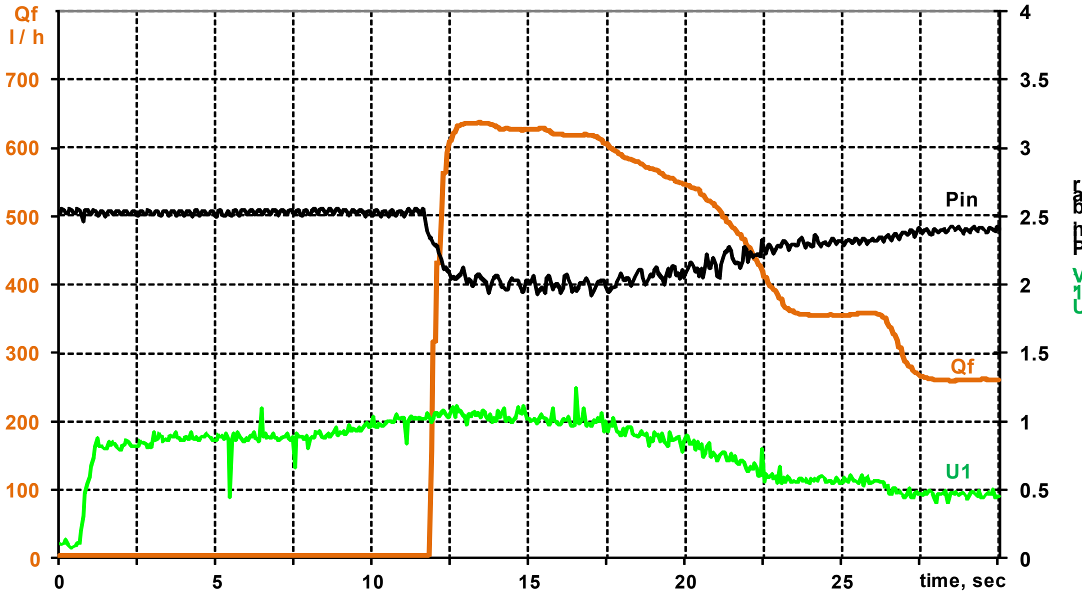

Fig. 7 Changes in FFS parameters when actuating the gear pump

The overload capacity is found on the basis of electric drive operation in the aircraft flight cycle. At the same time, the pump in maximum continuous flight operates at low speeds (30 ... 40% of max. speed), that increases the pump service life.

According to expert estimations, failures in electrically driven pumps are possible, mainly, due to failures in their electric drives and, most likely, in their electrical components. As a rule, installation of a second backup electric drive can't be proposed because of the double-weight system, although there are many patents aiming at improvement of fail-safety by this way which can be used only for ground systems.

Electric drive shall meet the following requirements for fail-safety:

- operation without changes in characteristics in case of one failure in electronic or electrical components (stator winding short-circuit or breakdown, faults in power-circuit limit switches, a rotor position sensor, a control unit, etc.)
- operation with a power decrease by 30% of max. power in case of one failure in mechanical components or two failures in electronic and electrical components.

The following options are studied for error compensation (failure management) in the electric drive: redundancy of the control unit or its computing section in combination with power-circuit limit switches, redundancy of power windings (double or triple redundancy), redundancy of phases (multiphase electric motors with > 3 phases).

Analysis of possible circuit configuration solutions aiming at an improvement of fail-safety of controlled permanent-magnet motors shows applicability of six-phase electric motors. Due to the increased number of phases, these electric motors have a low level of torque pulsations and rotor pulsations of current harmonics. They provide high fault-tolerance because in case of one-phase open fault (short circuit or breakdown) and even two-phase open fault, they can continue operation using the remaining phases with higher currents but with degraded pulsation characteristics. The main disadvantages of the multiphase drive are an increase in weight and dimensions, as well as the mutual interference of fields of different phases.

Microcontroller redundancy is usually provided by a two-channel configuration of the control system. Its specific feature is the need for primary and backup control modules (№ 1 and № 2 in Fig. 8), a diagnostic and automatic switchover module (failover unit) as well as digital buses for data transmission between the control modules to synchronize the microcontroller operation.

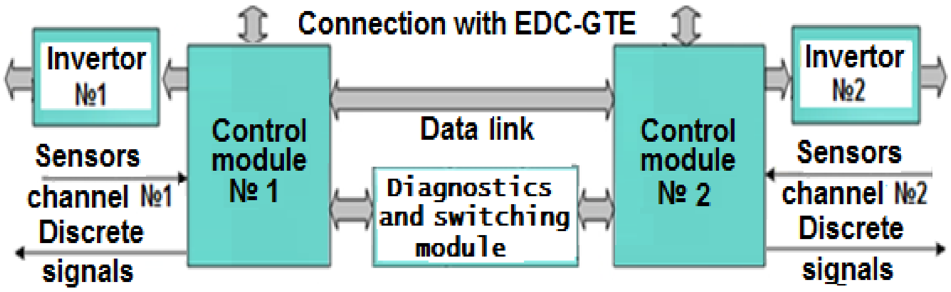

Fig. 8 Schematic redundancy diagram for the control unit computing section

Data received from current sensors and rotor angular position sensors are required for operation of Control Module 1 and Control Module 2. ON/OFF control signals are also duplicated. Switching over to the backup module is performed within one or several controller cycles and takes time from milliseconds to fractions of a second.

The following parameters and events are used in monitoring the channel operation: communication line breakdown, short circuits, values of supply voltage and supply current, lost communication, overheating of output module amplifiers, current overload, lost load, dynamic range overshooting, fuse triggering, actuation of interlocks and safety devices, continuity of communication lines with the input-output modules, checksum error, "freeze", etc. Channel switchover is normally performed by software.

A critical component of the valve electric motor is the rotor position sensor (RPS), which failure leads to rotation stop. In this connection it is necessary to switchover to a backup algorithm, e.g. a sensor-less switching algorithm for motor windings. These algorithms are based on indirect definition of motor rotor position, application of an electric drive mathematical model in the control unit, etc. Sensor-less switching algorithms can lead to limiting the time rate of changes for control signals.

Motor bearings are also critical parts and their state diagnostics is required, for example, by analyzing trends of vibration speeds at rotor rotational speed. If vibrations exceed permissible values, signal will be generated to decrease speed of the electric drive or its safe shutdown.

5 Extension of high-pressure lifetime

At present, the lifetime level of high-pressure pumps is the lowest among units of the automatic control system for GTE. Operation time at max. speed and max. pressure difference in the pump (i.e. "Takeoff" conditions) is a decisive factor for the gear pump lifetime. In the two-stage fuel supply system shown in Fig. 1 with series connection of electrically driven pumps, operation time in conditions with max. pressure difference in the high-pressure gear pump can be reduced by a differential pressure redistribution between high- and low-pressure pumps, in this way providing a power-saving mode.

This pressure difference redistribution is only possible in the fuel supply system with series connection of pumps, because the low-pressure pump will be designed for pumping pressure sufficient to ensure fuel supply to the combustion chamber if the high-pressure pump is failed. In "Takeoff" this pump can be switched over to a power-saving mode with maximum possible increase in pressure, while ensuring high pressure at the high-pressure pump inlet and, consequently, a decreased differential pressure in it. The power-saving mode is provided by operation of the low-pressure pump electric drive at the upper speed level, and the required fuel flow is provided by changing the high-pressure pump speed.

In the fuel supply system with series connection of low- and high-pressure pumps a centrifugal pump (CN) can be used as a high-pressure pump with considerably longer lifetime than the gear pump, but with lower efficiency at flow rates and pressure differences in the pump specific to an aircraft GTE. The centrifugal pump efficiency can be increased by a multi-stage configuration. For a single-stage centrifugal pump with 40-bar pumping pressure, 3410-kg/hr flow rate and 25000-rpm rotational speed, the pump delivery coefficient $\mathbf{n}_s$, is equal to ~ 30 and, consequently, the pump efficiency is ~30%; for a two-stage pump - $\mathbf{n}_s$ = 50.5 and efficiency = ~45%; for a four-stage pump - $\mathbf{n}_s$= 84.8 and efficiency =60 ... 70%. An increase in number of centrifugal stages by N-times with decreased pumping pressure by N-times can result in the centrifugal pump efficiency close to the gear pump efficiency. Variations of efficiency within "Idling-Takeoff" are negligible – from 44 to 60% (Fig. 9).

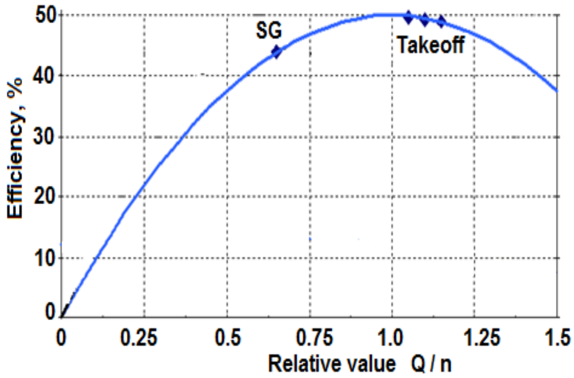

Fig. 9. Characteristics of the electrically driven centrifugal pump

As shown in Fig. 9, a decisive criterion for centrifugal pumps - flow-to-speed ratio (Q/n) - varies within 0.6 - 1.15 relatively to the design point (Q/n =1). These efficiency variations are caused by the fact that a decrease in fuel supply to an engine causes a decreased fuel pressure at pump outlets that calls for a decrease in the pump speed. As a result, changes in the pump operation mode in view of Q/n ratio are negligible.

6 Conclusions

1. Reliably of fuel supply systems for GTEs with electrically-driven pumps can be achieved by:

- application of a two-stage system with a series connection of electrically-driven high- and low-pressure pumps, and designing a startup line (or a bypass line in case of high-pressure pump failure) with check valves to ensure their interchangeability within a specified range of operation conditions (e.g. cruise flight and landing to ensure return to an airbase);

- regulation of electric drive speed used as a primary law for fuel flow control, and regulation of current in power windings - as a backup law;

- designing an electrically-driven pump with fuel cooled ED stator and rotor, without sealing the shaft between the pump and the electric motor to provide max. overload capacity and decreased weight of the electric drive;

- reliability of the valve electric drives with permanent magnets can be provided by multi-phase electric motors having a control unit with redundancy of a microcontroller, power-circuit limit switches, current sensors and angular rotor position sensors, with trending the vibration amplitudes in ED rotor speed harmonics.

2. Lifetime of electric pumps can be extended by a decrease in pressure difference by 25 ... 30% in the high-pressure pump through rotation the low-pressure pump in the two-stage fuel supply system, long-time operation of the pumps in the flight cycle at low speeds (30 ... 40% of max. speed), as well as application of multistage centrifugal pumps.

7 References

[1] Gurevich O., Gulienko A., Schurovskiy U. Demonstration Systems of the "Electric" Gas Turbine Engine.29th Congress ICAS, St. Petersburg, Russia; September 7-12, - 2014, - P.6.

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