CHARACTERISTICS OF SYSTEMS WITH ELECTRICALLY DRIVEN UNITS - EXPERIMENTAL STUDIES IN A GAS TURBINE ENGINE DEMONSTRATOR

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Abstract

The methodology and results of tests of electrically driven systems in a gas turbine engine (GTE) are outlined. Processes of their operational development with a digital automatic control system containing a GTE mathematical model are studied before the tests. Switchover from the main (standard) GTE control system with pumps driven by an accessory gearbox to the system with electrically driven units is provided without GTE shutdown. Characteristics of the systems in steady and transient conditions are presented. It is important to emphasize that this approach to testing makes possible to reduce work scope and improve test validity.

1 Introduction

As a rule, experimental studies of GTE control, fuel supply, and oil systems are performed at stand-alone semi-scale test rigs with feedback, where full-size devices operate with a mathematical model of an engine (MME). This is due to the fact that testing of these systems in an engine is usually limited to checking their performance in the main (standard) configuration or similar to it. In such a case, options for investigation tests are very limited.

At the same time, operation of system units in an engine makes it possible to improve test validity, because accuracy of test results for half-scale test rigs is not high due to an influence of numerous non-avoidable factors. They include, for example, the influence of parameters of test rig systems (long lengths of pipelines of fuel and pneumatic systems, power load methods of actuators, etc.). It is very difficult to ensure their interaction by the same way as in a GTE when changing flight conditions and engine operation mode.

Noticeable static and dynamic errors are caused by converters of electrical signals into physical values depending on parameters of operating process in the engine (rotational speed, gas pressure, and temperature) generated in its mathematical model. It is impossible to reproduce measurement specifics for control parameters associated, e.g. with effects of non-uniformities or pulsations.

The validity and information value of independent tests of GTE control systems and fuel supply systems are improved when they are tested in an engine.

2 GTE Electric Drive Control System

An electric-driven control system (EDCS) demonstrator was developed and tested by CIAM; its structure and characteristics of control units were chosen as applicable to the AI-25TL engine (Fig.1) used as the engine-demonstrator.

The EDCS contains a digital control unit (FADEC-type) with the following sensors: rotational speed (n_1, n_2), air pressure at the compressor outlet (P_2), and fuel flow (G_f), etc., as well as control units for actuators - electric drives for a gear pump and inlet guide vanes (CU GP and CU IGV), electromagnetic control valves for air bleed valves (ABV3 and ABV5) and for a cut-off valve (CV) controlling fuel supply to fuel nozzles depending on signals from a block of digital commands (BDC) of a digital controller.

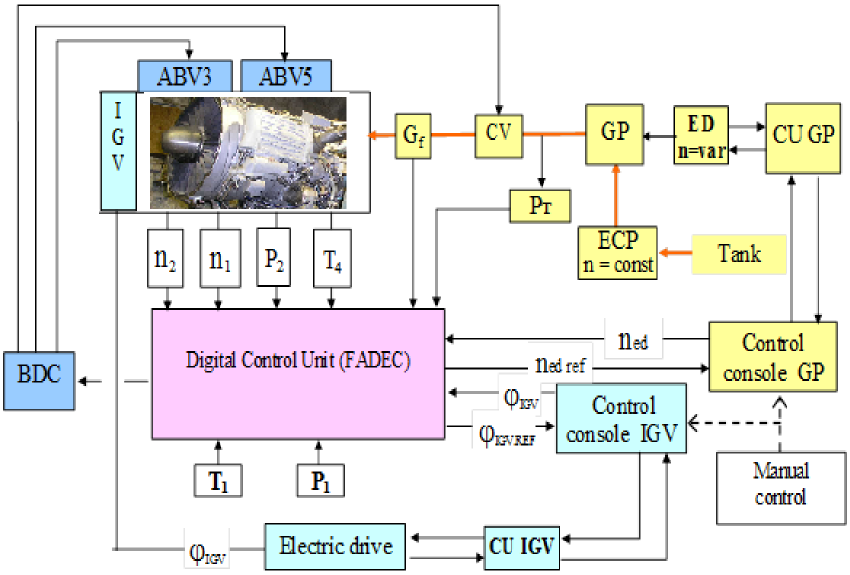

Fig. 1. Block diagram of EDCS

The digital control unit also contains a mathematical model of an engine (MME) to perform calculations of rotational speeds (n_1 and n_2) of engine rotors, thermogasdynamic parameters (temperature and pressure) in basic engine cross-sections, as well as operating parameters (thrust, specific fuel consumption, etc.) in specified flight conditions within a range of modes from idling to maximum in steady and transient conditions of engine operation.

These engine parameters are outputs of the model. Inputs of the engine model are flight conditions, Mach number, and a flight altitude, as well as air pressure and temperature at the engine inlet.

The model includes a set of fundamental equations of gasdynamics, thermodynamics, and mechanics written as unsteady-state equations.

The model takes into account an inertia of rotating masses, dynamic and gas-dynamic processes in various volumes (a bypass duct, a combustion chamber, etc.), a dependence of a specific heat ratio and gas constant on gas temperature and composition, compressor air bleeding, feeding back a portion of bleed air into a turbine flow passage, changes in combustion efficiency depending on gas composition and pressure, and other factors.

The model can make calculations of engine parameters with max. 1 ... 3% error in steady conditions or 2 ... 5% error in transient conditions in relation to specified initial data.

The initial data for the model development are characteristics of engine components and engine design parameters.

Photos and basic characteristics of the EDCS components are shown in Fig.2.

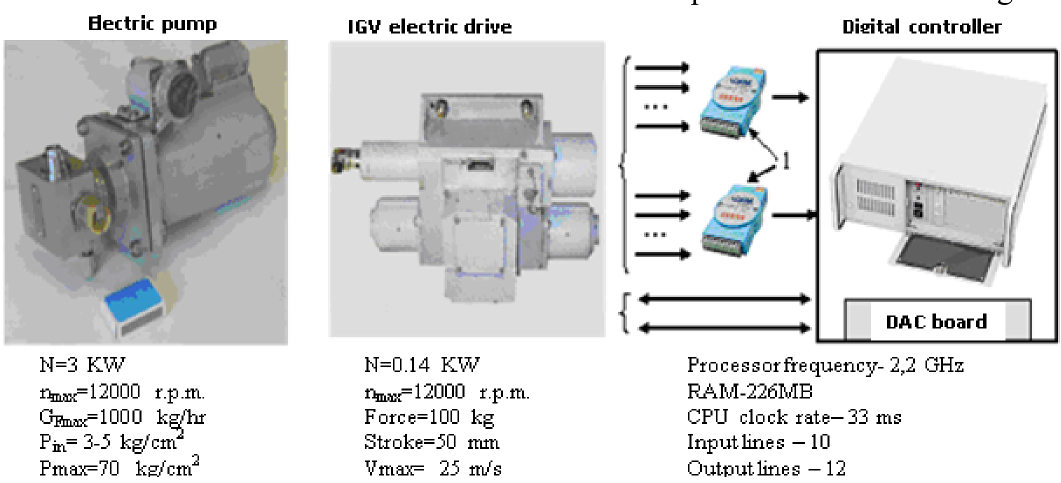

Fig. 2. Components of EDCS

The electric drive with ac converter-fed motor is used for rotation of the gear-type pump which control block provides control of the electric motor by providing settings of rotor rotational speed or current in the electric motor coils.

In the operating mode at the preset rotational speed of the electric motor shaft, signals of real-time rotational speed from r.p.m. sensor built in the electric motor as well as r.p.m. setting (U1 setting) from the control panel or from the GTE control system are sent to the controller inlet.

In the operating mode at the preset torque of the electric motor shaft, the current controller is in operation. Signals of real-time current from the current sensor and the current setting (U1 setting) from the control panel or from ACS are sent to the controller inlet. Based on the signal difference, an output is generated that sets up current in electric motor coils with limited max. value.

Use of the electric drive in the fuel system entails a capability for fuel metering for controlling parameters of working process in the engine when fuel flow value is a function of pump rotational speed (the system without metering device). Moreover, the fuel supply system should be also modified: there is no need in bleed and throttle valves for adjustment of fuel flow at the pump outlet with respect to engine consumption because there is no direct relationship between rotational speeds of the engine shaft and the pump rotor [2].

The guide vane drive mechanism is based on valve electric drive and roller-screw pair and completely displaces guide vanes within 0.5 sec; electric-pneumatic drive of air bypass control valves closes / opens bypass within 0.2- 0.3sec that provides stable engine operation at steady and transient regimes.

Application of the electric drive for rotation of compressor guide vanes makes it possible to reduce the number of precession spools-and–sleeves in automatic control system (ACS) components as well as connections in fuel pipelines, decrease fire risk(no kerosene in hydraulic cylinders), to eliminate the influence of the drive operation on the fuel supply system.

Location of EDCS components on the engine-demonstrator is shown in Fig. 3.

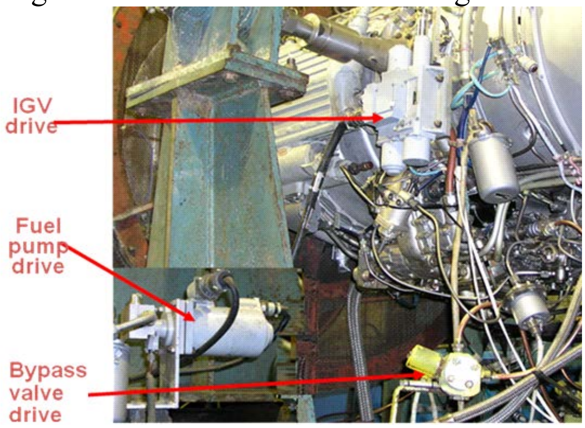

Fig. 3. Location of EDCS components on the engine

Effective studies of characteristics of new systems and units in GTE are possible with online changes in configuration of hardware connected to an engine-demonstrator. In this case, the test rig control system in the process of testing should provide reconfiguration of the engine hardware without engine shutdown. To ensure safety of tests during reconfiguration, the engine shall be able to switch back to operation from the main system.

This test rig was developed by CIAM, where the AI-25TL GTE with the hydromechanical control system (HMCS) was installed as the engine-demonstrator. The engine is equipped with variable inlet guide vanes (IGV) and air bleed valves in the 3rd and 5th stages of the high-pressure compressor (HPC); an air starter is used for start-up. Basic characteristics of the engine are the following: max. thrust - 17200 N, rotational speed in idling - 9550 rpm, total pressure ratio - 9.5, max. gas temperature at the turbine outlet - 715 °C, fuel flow - from 180 to 1100 kg/hr, acceleration time from idling to 95% take-off thrust on the ground - ≤12 s, in flight - ≥9 s. The test rig provides GTE tests at H = 0 ... 4000m, M = 0 with air flow up to 120 kg/s, at inlet air temperatures from -50 °C to +60 °C.

3 Characteristics of the engine-demonstrator fuel system

The fuel system of the test rig (Fig.4) ensures engine operation with a hydro-mechanical control system (HMCS) or with a new electric-driven control system (EDCS).

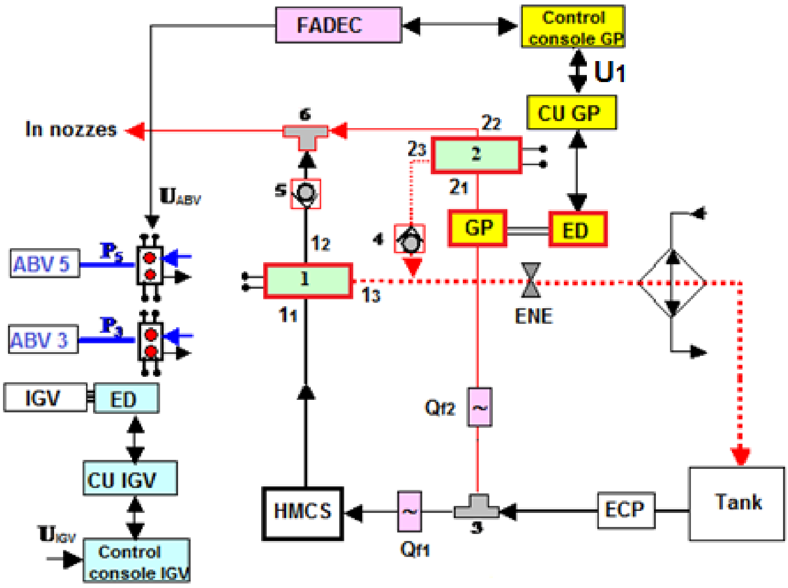

Fig. 4. Block-diagram of fuel supply to the engine-demonstrator
1, 2 - «EDCS - HMCS» three-way changeover valves; 4, 5 – back-pressure valves; 3, 6 – tees;
ENE – equivalent of engine fuel nozzles.

Fuel from the test rig tank is fed to the ECP boost fuel pump and then through the filter - to the inlet of the EDCS electric-driven pump and to the engine HMCS inlet. Operation of the systems is provided by the test rig assembly units – the ECP pump, Tee 3, that splits fuel flow from the test rig system to the pumps into two streams, and Tee 6, that merges fuel supply at the inlet of engine fuel nozzles. Fuel from the EDCS and HMCS pumps is supplied either to the engine nozzles or to the equivalent of fuel nozzles (ENE).

Switch-over of the fuel supply systems is provided by the three-way electromagnetic-controlled Valve 1 and Valve 2 connected via Inlet 1_1 and Inlet 2_1 to the outlet of HMCS and EDCS pumps. The initial state of the fuel supply system is "HMCS", when Outlet 1_2 of Valve 1 is connected to Tee 6, and Outlet 2_3 of Valve 2 - to ENE (Fig.4). It is possible to switch over from one system to another while the engine is running and the disconnected system is operating with ENE.

Valve 1 and Valve 2 have a trigger characteristic, and after voltage supply to its electromagnet, the valve spool shifts and connects the valve inlet to a respective outlet; in this case, supply voltage of the electromagnet is Off and the power supply circuit is connected to execute the next control command.

This state is not changed until receipt of a control command.

Measurements and processing of parameters in the information and measurement system of the test rig are based on three key algorithms: acquisition and processing of parameters in unsteady modes, acquisition and processing of parameters in steady modes, and continuous data recording.

4 Methodology of engine-demonstrator testing

The methodology for experimental studies is developed, which makes possible to start up the engine demonstrator with the basic configuration of all its systems and operate with them, then switch over to operation with another system, and switch back. The methodology includes two stages: a preparatory (technological, Fig.5A) stage and a stage of operation with a new system (Fig.5B).

The figure below shows a hydromechanical control system for HMCS engine as the main system, and a FADEC-type digital system with an electrically driven pump for fuel supply to the engine as a new system.

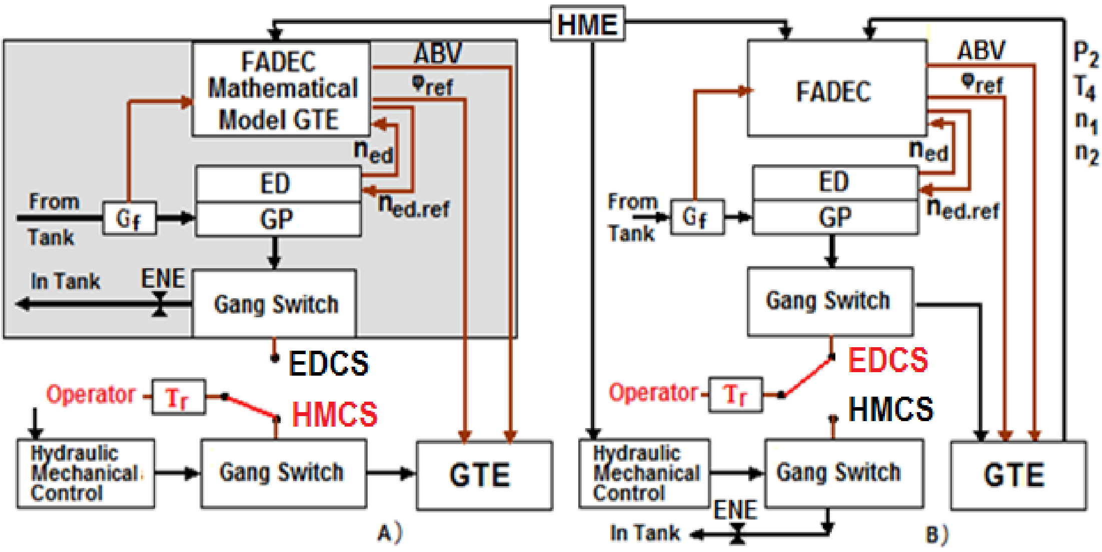

Fig. 5. Schematic diagram of tests of new systems in GTE architecture.
A) - preparatory stage, B) – operation with a new system

The tests are controlled by an operator, who connects to HMCS engine the main control system or the new digital FADEC system by changing the position of "Tr" toggle-switch in the Gang Switch. The Gang Switch contains two-position three-pass valves with electrical control.

The task of the preparatory stage is checking the operability of all new units before their testing in the engine architecture. For this purpose, the checking is provided with a digital FADEC controller containing a mathematical model of the engine (MME). The engine operation mode can be changed by sending a control signal from the manual engine control lever (HME) to the controller inlet which sends $\mathbf{n_{ed.ref}}$ control signal to the electric drive (ED) of the gear pump (GP) and φ_{ref} signal to devices in the engine flow passage. The signal of actual fuel flow (G_f) is transmitted to MME, while the gear pump (GP) works with the engine nozzle equivalent (ENE) and fuel from the GP feeds back to a tank. When changing the engine operation mode, control of operation of compressor guide vanes and actuation of air bleed valves (ABV) is checked simultaneously.

The tests are controlled by an operator who, by changing the position of the "Tr" toggle switcher in the mode selector unit (the Gang Switch), connects the main hydromechanical control system (HMCS) or the electric-driven EDCS with the FADEC digital controller to the GTE (Fig. 5). The Gang Switch contains two-position three-way valves with electrical control.

For operation at the preparatory stage, the "Tr" toggle switcher is in the HMCS position, when Inlet 1_1 of Valve 1 is connected to Outlet 1_2 for fuel supply from the HMCS to the engine nozzles, and Inlet 2_1 of Valve 2 - to Outlet 2_3 for fuel supply from the EDCS pump to the ENE and then to the test rig. The engine is not operating, and the HMCS back-pressure valves prevent fuel supply to the combustion chamber injectors.

Transmission of commands to switch on the electric-driven units is provided by the digital controller that generates control signals for the ED electric drive of the GP gear pump ($n_{ed.ref}$) and for compressor mechanical devices (φ_{ref}) by the same way as in normal operation. Since the engine is not operating, the engine parameters (P_2, T_4, n_2) required for the controller are taken from the mathematical model of the engine (MME).

The required fuel flow signal is sent to the controller and to the MME, and fuel from the gear pump is supplied to the ENE and back to the tank but not to the engine. The actual fuel flow signal (G_f) is sent to the MME, and the fuel supply system reaches the required operation mode.

Fig. 6 shows the transient process for fuel consumption (Q_f) when the U_1 control signal is transmitted to switch ON/OFF the electric drive of the pump operating for the ENE.

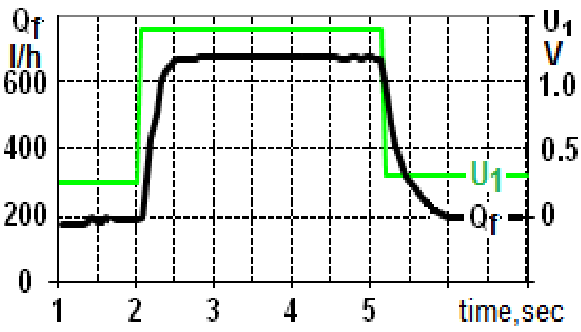

Fig. 6. Pump ON/OFF

Time of fuel flow changes from minimum to maximum is 0.5 s.

When a set point of HPC rotational speed is reached, actuation of the air bleed valves (ABV) and changes in the IGV position are checked.

When simulating failure of one of the sensors - P_2, T_4, or n_2, the controller uses values of a respective parameter from the mathematical model of the engine (MME).

Upon successful completion of verification operations at the preparatory stage, the engine starts up and reaches the idling mode. The engine operation mode is changed by sending a control signal from the manual engine control lever (HME) to inlets of EDCS and HMCS controllers.

Changeover from the hydromechanical system to the electric-driven system is provided in idle mode (or higher) by switching over the "Tr" toggle switcher to the EDCS position.

In this case, Inlet 2_1 of Valve 2 is connected to Outlet 2_2, and Inlet 1_1 – to Outlet 1_3 ("Tank"). Fuel from the electric-driven gear pump is supplied to the engine, and fuel from the HMCS outlet is fed back to the tank via the ENE.

Back-pressure Valve 4 and Valve 5 prevent fuel flow from one system to another (Fig. 4).

The FADEC controller receives signals from the GTE sensors for the following parameters: n_1, n_2 - rotational speeds of low- and high-pressure rotors, T_4 - gas temperature at the turbine outlet, P_2 - air pressure at the HPC outlet, etc.

5 Test results

Engine acceleration / deceleration. Transient processes of changing the engine parameters with time when HME increases from n_2 = 57% to n_2 = 95% within 1 s (the acceleration process) and back within 1 s (the deceleration process) are shown in Fig. 7.

The EDCS system is used, where rotational speeds of electric drives are adjustable. The processes take place without overshooting in parameters; acceleration time is ~8 s.

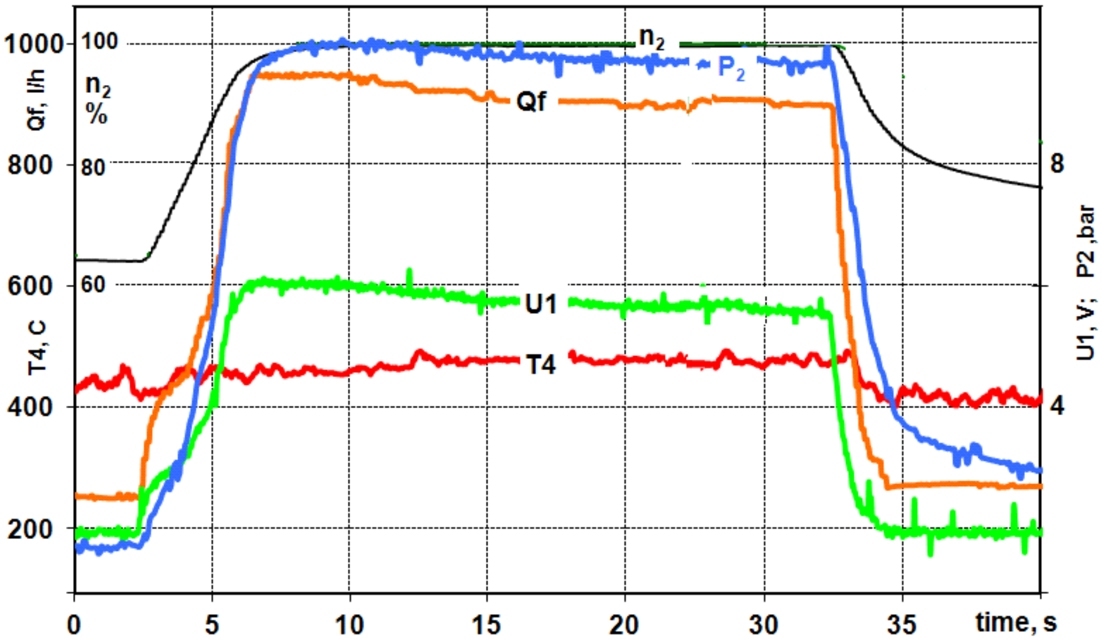

Fig. 7. Changes in engine parameters for acceleration / deceleration with EDCS

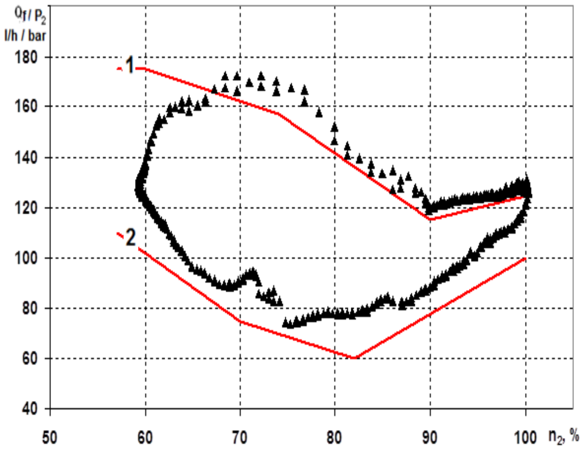

Fig. 8. Control programs for acceleration / deceleration with EDCS

Fig.8 shows the specified fuel flow control programs: Line 1– for acceleration and Line 2 – for deceleration in $Q_f/P_2 = f(n_2)$ coordinates..

Implementation of Program 1 and Program 2 is shown by indices.

The processes with HMCS system have over / undershooting by 50 / 8 l/hr in fuel flow and 60 / 35°C in gas temperature (Fig. 9).

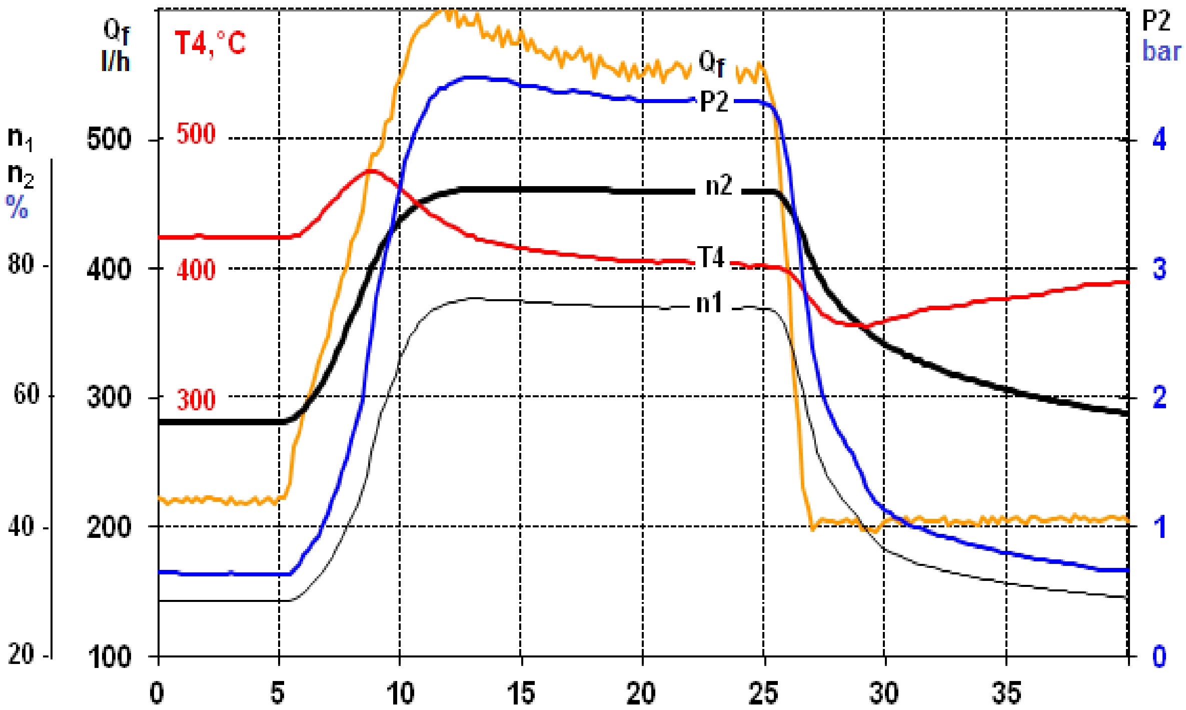

Fig. 9. Changes in engine parameters for acceleration/deceleration with HMCS

Fig. 10 shows transient process for parameters of IGV control units and ABV5 and ABV3 valves during acceleration. The digital controller generates a signal to open the IGV and close the ABV5 at 7.25-s time point at n_2 = 75.6%, and to close the ABV3 - at 8.3-s time point at n_2 = 87%.

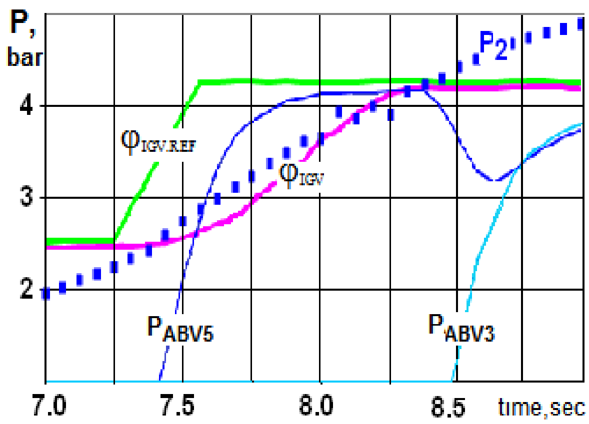

Fig. 10. Transient processes for IGV and ABV parameters during acceleration

Total IGV changeover time is 1.2 s as evidenced by changes in φ_{IGV} parameter characterizing movement of the electric drive stem. Pressure in the ABV control chamber begins to increase in 0.1 ... 0.2 s after receipt of the control command. In the transient mode, the IGV and ABV actuation has no effect on the P_2 pressure rise rate in the combustion chamber.

Transient processes in variation of engine parameters (n_2 - HPC rotational speed, Q_F – fuel consumption, U1 - control signal to the pump electric drive and T4 – gas temperature at the HPT outlet) when changing the r.p.m. controller setting ($n_{2\ set}$) by 5 % (“narrow” changes) and when increasing $n_{2\ set}$ from 62 % to 100 % (acceleration process) and decreasing $n_{2\ set}$ (deceleration) (“wide” changes) are shown in Fig. 7 and Fig.11. Transient process in variation of controlled variable (n_2) are smooth; the control signal from the control unit is processed by the electric pump drive almost without a delay (see U1 and Q_F in Fig. 7). Transition time from 62% n_2 to 95% n_2 is 3.2 s that is in compliance with engine requirements specifications.

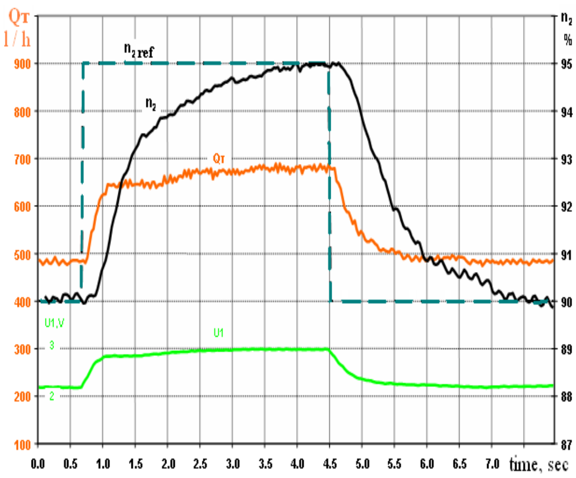

Fig. 11. Transient processes of engine parameters ("narrow" changes)

GTE shutdown. Transient processes for engine parameters during shutdown are shown in Fig. 12. In this case, the processes with the EDCS system are indicated by lines, and with HMCS - by indices. Shutdown time is almost the same. Shutdown is provided by sending a zero control signal to the pump electric drive or switching off its power supply. Fuel flow decreases to zero within ~0.8s.

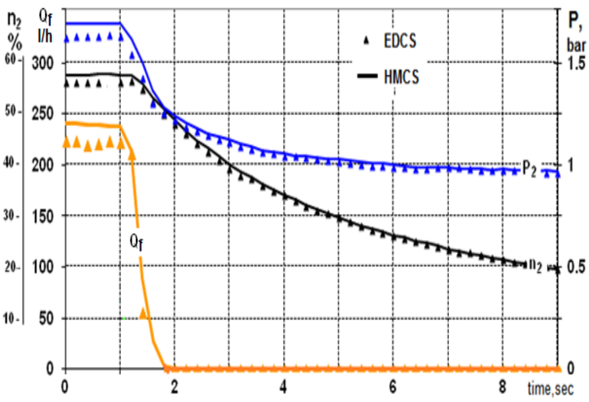

Fig. 12. Transient processes during engine shutdown

GTE start-up. When the engine starts up, the starter rotates the HPC rotor, and the controller at n_2 = 24% (12 s) sends U_1 command to the pump electric drive corresponding to 250 l/hr fuel flow. The inlet pipeline of fuel nozzles starts filling, fuel flow increases to 405 l/hr, and after filling, fuel flow smoothly decreases to the set value. Transient processes for engine parameters during startup are shown in Fig.13. A point that should be mentioned is undershooting in P_{in} at the GP inlet at the time point of flow increase in the pump.

The results of calculations and experimental studies of the characteristics of control systems, fuel supply and lubrication developed with using electrical technology, have shown that such systems provide a gas turbine engine work with the required characteristics for steady state and transient conditions.

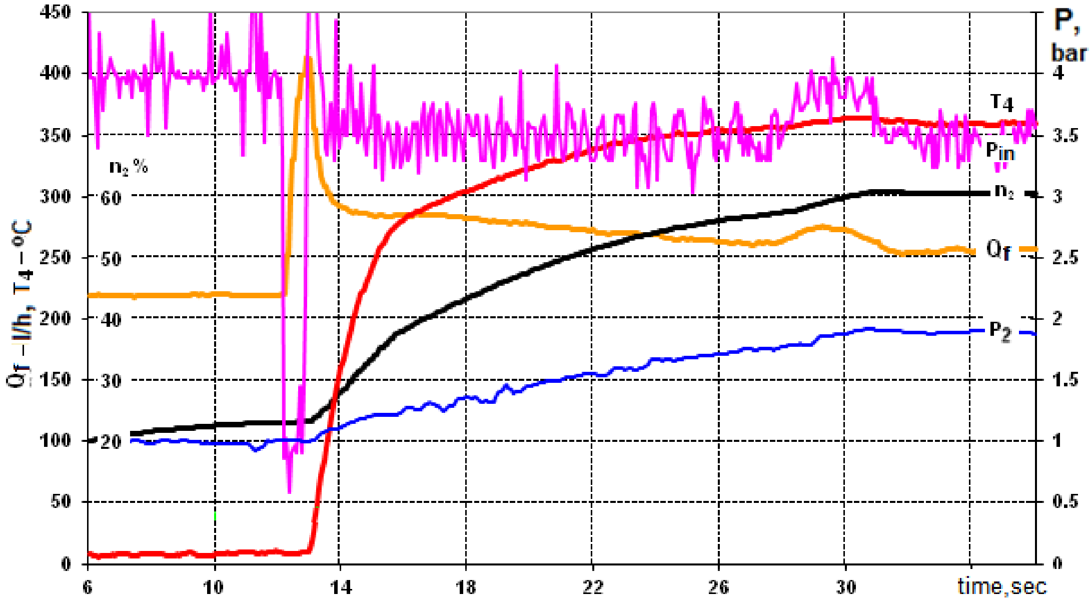

Fig. 13. Transient processes during engine startup with the EDCS system

6 Conclusions

1. Based on the climatic altitude test chamber, an adaptive test facility is developed for testing. It ensures studies of characteristics of electrically driven control, fuel supply, and oil systems both in an engine-demonstrator and independently in a closed circuit with a mathematical model of an engine when the fuel supply system operates with the engine nozzle equivalent.

2. The results of experimental studies have shown usefulness of this approach to tests of new systems in the GTE architecture. For example, connection of the fuel supply system with an electrically driven pump made us possible to develop main and backup control laws for rotational speeds of the electric drive as well as to check the system operation in emergency conditions, etc.

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, ID 2014_0218, 2014, - p.6.

[2] Gurevich O., Gulienko A. Methods for improving the reliability of fuel supply system of gas turbine engines with using electrically driven pumps // 30th Congress ICAS, Daejeon, Korea, September 25–30, ID 2016_0163, 2016, - p.9.

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