TURBOSHAFT-TYPE APU FOR AIRCRAFT AS CONTROLLED OBJECT

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Abstract: *This paper describes a case study of an aircraft auxiliary power unit (APU) considered as controlled object. Considering the specific case of a TG-16M power unit (which is an embedded system: a gas turbine turboshaft and an electrical 28 V DC generator), one has established the mathematical model of this system, based on its non-linear motion equations; operating with the finite difference method, one has obtained the linear and adimensional form of the mathematical model. Equations' co-efficient were experimentally established and/or calculated, during the ground lab tests of a TG-16M at the Aerospace Engineering Laboratory, University of Craiova. Based on the system's mathematical model, one has also performed some studies concerning its stability and quality, using Matlab® Simulink simulations.*

Keywords: *APU, gas turbine, fuel, rotational speed, control, electrical power, generator.*

1. INTRODUCTION

An auxiliary power unit (APU) is a small gas turbine engine that provides electrical power and/or compressed air to aircraft consumers, which enables them to operate autonomously, without reliance on specific ground support equipment (such as an electrical power unit/battery/generator, an external air-conditioning unit, or a high pressure air unit/battery).

This "supplementary" power is used to start the main propulsion engines, to provide pressurized air for aircraft environmental control systems, to provide electrical power for aircraft lighting, avionics and on-board galleys on the ground and, additionally, to provide backup and emergency power in flight [3]. APUs can provide power for almost all functions of the airplane while it is on the ground, except propulsion.

The main and most important purpose of the APU is to provide the power to start the aircraft main engine(s). An aircraft's gas turbine engine needs to be accelerated to rotate at an extremely high speed for it to provide an adequate amount of air compression to keep it spinning.

Depending on its destination and design, the APU can provide electric power, hydraulic power, pneumatic power or all three of them. Connecting APU to a hydraulic pump, it allows the crew to operate hydraulic equipment (such as the flight controls, aerodynamic brakes or flaps). Having one of these functions, such an APU is also useful for a backup, if there is an engine failure. APUs are critical to aircraft safety, as they supply backup electricity, as well as the compressed air, in place of a failed main engine generator, or of a dead engine.

Small airplanes do not need an APU, as those engines are started using an electric motor (electric starter), supplied by batteries. Meanwhile, big aircrafts are started by an air turbine motor or powerful electric starters and thus the need for the APU to power

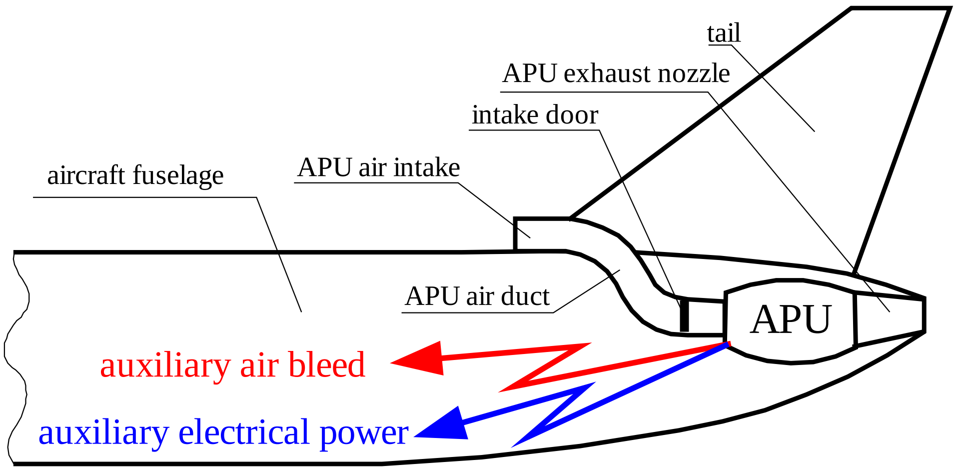

FIG. 1. APU's positioning on aircraft

them. Before the engine gets turned, one needs to start the APU (usually by battery or a hydraulic accumulator).

APU's are often positioned in the tails of aircraft (rear fuselage, as Fig. 1 shows), in the rear of one of engines' nacelles, or in the landing gear bay, ranging from larger turboprops to jets. On most jets, the APU is installed in the far aft tail-cone section, so as to isolate it as much as possible from other systems in the event of an APU fire. Like the aircraft's main engines, an APU must be installed behind a firewall. It also needs its own fire detection and extinguishing system.

The APU can be started utilizing only the aircraft battery(s) (accumulators) and, once running, it will provide to aircraft systems electrical power, hydraulic pressure, as well as bleed air for air conditioning (and/or for main engine(s) start, depending on its (their) starting solutions).

Because the APU is often operated on the ground, dual fire-control panels are sometimes installed, one in the cockpit and one accessible from the aircraft's exterior. This allows an APU fire to be fought from either location. Since an APU is usually not closely monitored by the crew once it is started, most are designed to shut down automatically in case of a fire or loss of oil pressure [3].

Some APUs are only for ground use (engine start, air conditioning), but if certified for use in flight, the APU can be used, as required, to provide an additional source of electrical power in the event of the loss of an engine generator. It can also be used as a source of bleed air for supplementary air conditioning, as well as for starter assist for an in-flight engine relight, or to power the air-conditioning packs if the event conditions or company policy dictate that the takeoff should be conducted with the main engine bleed air turned off. The APU is normally left off in flight, but it may be turned on for certain long-haul flights, or for overwater (transoceanic) flights, as an extra precaution.

2. SYSTEM'S PRESENTATION

The studied TG-16M APU is turboshaft-type, similar to a turboprop engine (obviously, without propeller), which spins up a dedicated 28 V DC electrical generator via a planetary gear. It operates as auxiliary electrical power source for an airplane (such as An-24T short-haul passenger airplane, or the old Il-18 medium-haul passenger airplane); it is positioned in the rear of starboard AI-24 engine's nacelle.

As Fig.2 shows, APU is broken up into three main sections – the power section, the gearbox and the electrical generator. The power section consists of the gas generator

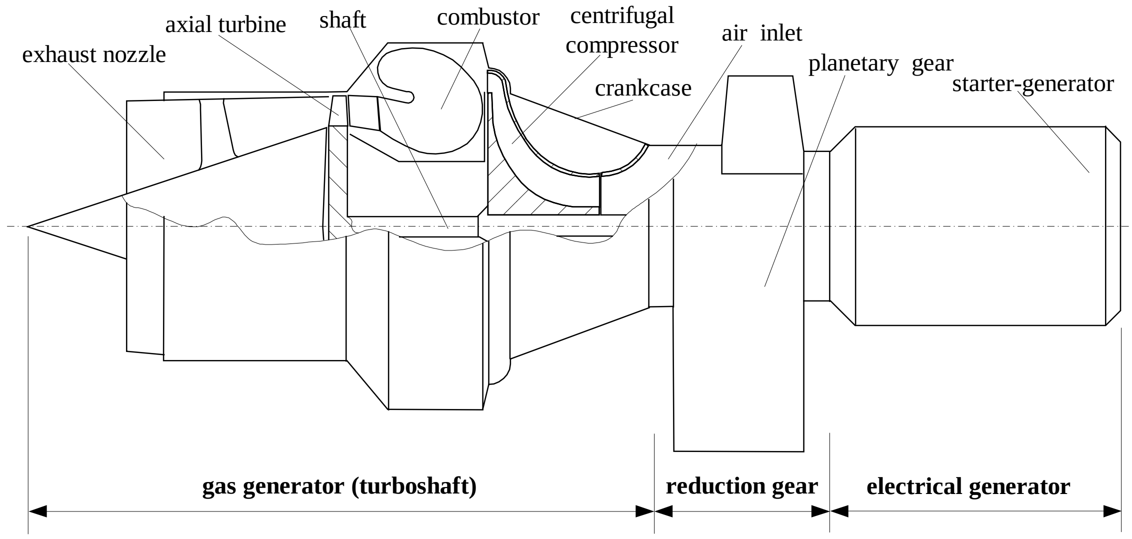

FIG. 2. APU's main parts

portion of the engine and produces all the power for the entire APU (engine's compressor, reduction gear and electrical generator).

APU's main shaft is driven by a single stage axial turbine (which is the gas generator turbine); it spins up the engine's centrifugal compressor, as well as the electrical generator via the planetary reduction gear. The gas generator has a compact inverted flow combustor, where the injected fuel is mixed with the compressed air (delivered by the compressor) and burned into hot gases, which are expanded in the engine's turbine, then discharged through the exhaust nozzle.

So, turbine's mechanical work should cover the necessary work of the compressor, of the gear, as well as of the electrical generator.

3. NON-LINEAR MOTION EQUATIONS

Non-linear mathematical model consists of APU-system main parts' non-linear equations; relevant main parts are: APU's main shaft, rotational speed transducer, fuel pump and fuel control system. Figure 3 contains fuel system's technical schematic.

3.1. Shaft equation. Shaft motion equation involves turbine$\left(M_T\right)$, compressor$\left(M_C\right)$, gear$\left(M_g\right)$, friction$\left(M_{fr}\right)$ and electrical generator$\left(M_{EG}\right)$ torques, as follows:

$$M_T - M_C - M_g - M_{fr} - M_{EG} = \frac{\pi J}{30}\frac{\mathrm{d}n}{\mathrm{d}t}, \tag{1}$$

where J is spool's axial moment of inertia and n – shaft rotational speed.

Assuming that M_g and M_{fr} torques are nearly constant and low values, they may be neglected for further studies. Meanwhile, one can affirm that turbine torque (M_T active torque) depends on the injection fuel flow rate Q_i and on the shaft speed n; compressor torque M_C depends only on the shaft speed [11, 12], while generator torque M_{EG} depends both on the shaft speed and on the load current amperage I_{cg} (M_C and M_{EG} being resistant torques).

3.2. Fuel control system equations. As fig. 3 shows, injection fuel flow rate Q_i (which supplies engine's combustor) is established as the difference between pump's

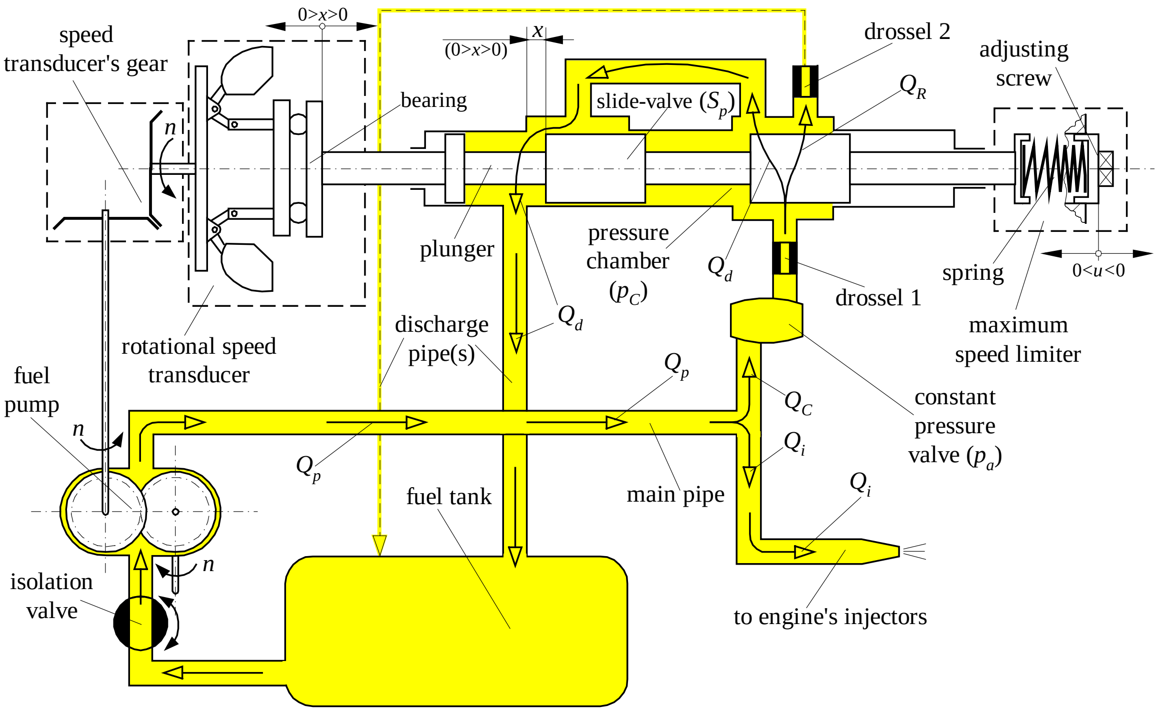

FIG. 3. APU's fuel system

flow rate Q_p and control flow rate Q_C (which is recirculated and sent to the fuel tank). In the pressure chamber the control flow rate is split into two streams: Q_R – through the second drossel and Q_d – through the variable slot of plunger's slide valve and further through the discharge pipe back into the fuel tank. So, discharged flow rate Q_d depends on the plunger's displacement *x*, which results from engine's effective speed *n* and from preset speed value n_p (given by the adjusting screw's displacement *u*).

Motion equation for the fuel system are, as follows:

$$Q_i = Q_p - Q_C, \tag{2}$$

$$Q_C = \mu_d \frac{\pi d_1^2}{4}\sqrt{\frac{2}{\rho}}\sqrt{p_a - p_C}, \tag{3}$$

$$Q_R = \mu_d \frac{\pi d_2^2}{4}\sqrt{\frac{2}{\rho}}\sqrt{p_C - p_{dc}}, \tag{4}$$

$$Q_d = \mu b x\sqrt{\frac{2}{\rho}}\sqrt{p_C - p_{dc}}, \tag{5}$$

$$Q_C - Q_R - Q_d = S_p \frac{\mathrm{d}x}{\mathrm{d}t} + \beta_f V_C \frac{\mathrm{d}p_C}{\mathrm{d}t}, \tag{6}$$

where p_a is the fuel supplying pressure (assumed as constant, because of the constant pressure valve on the main pipe), p_C – command pressure, p_{dc} – discharging pipes fuel pressure (very low value, comparing to p_a and p_C, so negligible), μ, μ_d – flow co-efficients, d_1, d_2 – drossel's diameters, S_p – piston (slide-valve) surface area, ρ – fuel density, β_f – fuel compressibility co-efficient (practically null, so negligible, as the terms involving it), V_C – pressure chamber's volume, b – slide-valve's discharge slot width.

For further studies the above-presented equations should be simplified, by linearisation and adimensionalization. Meanwhile, one has to consider for the mathematical model the fuel pump's equation, as well as the speed transducer equation.

4. SYSTEM'S MATHEMATICAL MODEL

4.1. Linearised motion equations. Non–linear equations can be brought to a linear form, using the finite difference method, assuming the small perturbation hypothesis; formally, any variable or parameter X should be considered as $X = X_0 + \Delta X$, where X_0 is parameter's steady state regime's value, ΔX – parameter's deviation and $\overline{X} = \frac{\Delta X}{X_0}$ the non-dimensional deviation. Consequently, the above-presented equations become

$$\left(\frac{\partial M_T}{\partial n}\right)_0 \Delta n + \left(\frac{\partial M_T}{\partial Q_i}\right)_0 \Delta Q_i - \left(\frac{\partial M_C}{\partial n}\right)_0 \Delta n - \left(\frac{\partial M_{EG}}{\partial n}\right)_0 \Delta n - \left(\frac{\partial M_{EG}}{\partial I_{cg}}\right)_0 \Delta I_{cg} = \frac{\pi J}{30} \frac{\mathrm{d}}{\mathrm{d}t} \Delta n, \qquad (7)$$

$$\Delta Q_i = \Delta Q_p - \Delta Q_C, \qquad (8)$$

$$\Delta Q_C = -\mu_d \frac{\pi d_1^2}{4} \sqrt{\frac{1}{2\rho(p_a - p_{C0})}} \Delta p_C = -k_{CC} \Delta p_C, \qquad (9)$$

$$\Delta Q_R = \mu_d \frac{\pi d_2^2}{4} \sqrt{\frac{1}{2\rho p_{C0}}} \Delta p_C = k_{RC} \Delta p_C, \qquad (10)$$

$$\Delta Q_d = \mu b \sqrt{\frac{2 p_{C0}}{\rho}} \Delta x + \mu b x_0 \sqrt{\frac{1}{2\rho p_{C0}}} \Delta p_C = k_{dx} \Delta x + k_{dC} \Delta p_C, \qquad (11)$$

$$\Delta Q_C - \Delta Q_R - \Delta Q_d = S_p \frac{\mathrm{d}}{\mathrm{d}t} \Delta x. \qquad (12)$$

4.2. Non-dimensional linear equations. Using some appropriate chosen amplifying terms, the above-presented linearised equations can be transformed in non-dimensional forms; after applying the Laplace transformation, one obtains the system's linear non-dimensional mathematical model, as follows:

$$(\tau_m \mathrm{s} + 1)\overline{n} = k_f \overline{Q_i} - k_{cg} \overline{I}_{cg}, \qquad (13)$$

where $k_{mR} = \left(\frac{\partial M_C}{\partial n}\right)_0 + \left(\frac{\partial M_{EG}}{\partial n}\right)_0 - \left(\frac{\partial M_T}{\partial n}\right)_0$, $\tau_m = \frac{\pi J}{30 k_{mR}}$, $k_f = \frac{1}{k_{mR}} \frac{Q_{i0}}{n_0} \left(\frac{\partial M_T}{\partial Q_i}\right)_0$ and

$$k_{cg}=\frac{1}{k_{mR}}\frac{Q_{i0}}{I_{cg0}}\left(\frac{\partial M_{EG}}{\partial I_{cg}}\right)_0;$$

$$\overline{Q}_i=\overline{Q}_p-\overline{Q}_C, \tag{14}$$

$$\overline{Q}_C=-k_{QC}\overline{p}_C, \tag{15}$$

$$(\tau_x s+1)\overline{x}=\frac{1}{k_{xC}}\overline{p}_C, \tag{16}$$

where $k_{QC}=k_{CC}\dfrac{Q_{C0}}{p_{C0}}$, $k_{xC}=\dfrac{x_0}{(k_{CC}-k_{RC}-k_{dC})p_{C0}}$, $\tau_x=\dfrac{S_p}{k_{dx}}$.

Together with Eq. (13), (14) and (15), in order to build the mathematical model, one has to consider also fuel pump's equation (16), as well as transducer's equation (17) (together with their own annotations, given by [12]):

$$\overline{Q}_p=k_{pn}\overline{n}, \tag{17}$$

$$\overline{x}=k_{es}\overline{n}-k_u\overline{u}. \tag{18}$$

Some observations should be made, concerning the above presented equations. Terms containing p_{dc} and β_f in Eq (4), (5) and (6) can be neglected. Meanwhile, the term containing $\overline{u}$ can be excluded, because adjustments concerning maximum engine speed value are made during ground tests.

System's block diagram with transfer functions, built using Eq. (13)…(18), is depicted in Fig. 4.

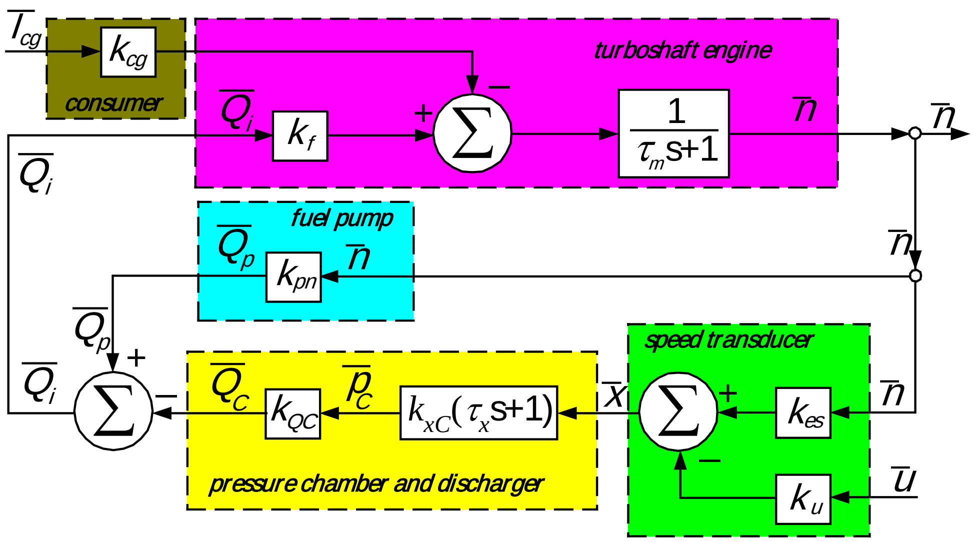

FIG. 4. System's block diagram with transfer functions

4.3. System's transfer function. The above-mentioned equations may be transformed into a much simpler single equation, which expresses the dependence $\bar{n} = f\left(\bar{I}_{cg}\right)$ and represents system's transfer function:

$$\left[(\tau_m - a\tau_x)\mathrm{s} + 1 - k_f k_{pn} + a\right]\cdot \bar{n} = -k_{cg}\bar{I}_{cg}, \tag{19}$$

equivalent to

$$\bar{n} = -\frac{k_{cg}}{(\tau_m - a\tau_x)\mathrm{s} + 1 - k_f k_{pn} + a}\bar{I}_{cg}, \tag{20}$$

where $a = k_{QC}k_{xC}k_{es}$, so the transfer function expression is

$$H_n(\mathrm{s}) = -\frac{k_{cg}}{(\tau_m - a\tau_x)\mathrm{s} + 1 - k_f k_{pn} + a}. \tag{21}$$

5. SYSTEM'S STABILITY AND QUALITY

System's transfer function is a first order one; for system's stability it is compulsory that its characteristic polynomial co-efficients have the same sign. Consequently, system's stability condition should be

$$(\tau_m - a\tau_x)(1 - k_f k_{pn} + a) > 0. \tag{22}$$

The term a is strictly positive (because of its definition formula(s)); meanwhile, from [11] and [12] it results that, in order to obtain a stabile engine-fuel pump connection, the term $1 - k_f k_{pn}$ must be strictly positive. Consequently, from Eq. (22) only the first term remains to be discussed, so $\tau_m - a\tau_x > 0$, which gives (considering formulas for a and τ_m)

$$S_p < \frac{k_{dx}}{k_{QC}k_{xC}k_{es}}\tau_m. \tag{23}$$

If $1 - k_f k_{pn} < 0$, the engine-fuel pump connection is unstable, which means that a supplementary condition is required, in order to keep the same condition (23). Consequently, for $1 - k_f k_{pn} + a > 0$, the supplementary condition is

$$a > \left|1 - k_f k_{pn}\right|, \tag{24}$$

otherwise the term $\tau_m - a\tau_x$ should become negative, and the (23)-condition becomes

$$S_p > \frac{k_{dx}}{k_{QC}k_{xC}k_{es}}\tau_m. \tag{25}$$

System's quality was studied for two situations: a) idling engine (without generator's load) b) step input of the electrical load $\bar{I}_{cg}$; results (step responses) are presented in Fig. 5 and were calculated using a Matlab-Simulink simulation, based on system's block diagram with transfer functions (in Fig. 4). System's co-efficients were experimentally and analytically determined, using a ground test facility for an APU (TG-16M type).

CONCLUSIONS

The paper has studied an APU as controlled object. The APU consists of a single shaft turbo-engine which spins up an electrical generator through a planetary gear. From its non-linear motion equations one has determined the linear non-dimensional mathematical model, as well as its transfer function.

The above studied system is a first order one, its transfer function having a first-degree characteristic polynomial, which has simplified its stability studies. One has obtained a condition for the stability, which gives an information about how to choose the plunger's slide valve frontal surface area S_p with respect to the gas turbine engine time constant τ_m and to the gas turbine engine's fuel system geometry (effective diameters), as well as to flow rate co-efficients values.

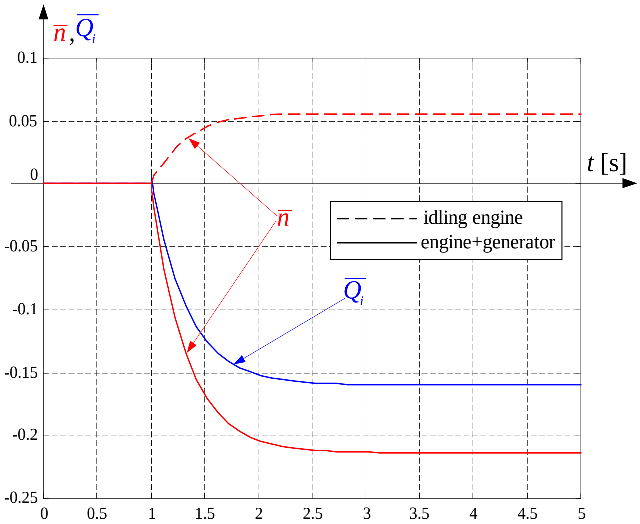

FIG. 5. System's quality (time step response)

System's quality studies shows that both the idling engine and the embedded system engine+generator have stabile aperiodic behavior, as seen in Fig. 5. The system is affected of static errors (positive for idling engine, negative otherwise), especially when the generator supplies external consumers, the bigger the consumers' electrical power are.

This study was realized only for ground test operation, but it may be extended to other APUs, as well as for some different flight regimes.

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