CONTROL OF HELICOPTER PARALLEL HYBRID PROPULSION SYSTEM

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ABSTRACT

Helicopter and engine manufacturers have been conducting R&T work for several years to design and improve parallel hybrid-electric propulsion system for rotorcrafts. A significant part of the benefits of hybridization is directly dependent on the control system. The hybrid power sharing control solution presented herein is designed as an integral control system of an electrical and a turboshaft engine, powering the helicopter main gearbox in parallel. The present paper elaborates the numerous concurrent objectives and mandatory constraints the hybrid propulsion system must fulfill. Then a global control architecture is proposed to handle all this objectives and to tackle possible conflicts by priorization logics. Finally, illustrating results obtained on a representative hybrid engine test bench are presented. The first case study deals with the safeguarding of the propulsion battery's energy. The second test scenario focuses on the automatic takeover of the backup electrical engine after an in-flight shut down of the main turboshaft engine. The control concept highlighted here offers interesting flexibility in managing multiple objectives and minimizes the risk of adverse interaction between the two power sources.

1 NOTATION & CONVENTION

Symbols:

N1	Gaz generator speed of the turboshaft, rpm
NR	Rotation speed of the H/C main rotor, rpm
R_i^*	Controller reference setpoint or limit associated with objective n°i
SOCmin	Minimum limit of the battery state of charge, kWh
SOCfbk	Feedback state of charge of the battery, kWh
T45	Exhaust gaz temperature of turboshaft, K
TQts	Torque of the turboshaft, Nm
TQm*	Torque setpoint of the electrical engine, Nm
TQm_i	Individual torque command dedicated to the i^{th} objective, Nm
XPC	Position of the collective pitch handle, %
Y_i	Controller feedback variable, associated with objective n°i

Acronyms:

AC	Alternative Current
BMS	Battery Management System
DC	Direct Current
H/C	Helicopter
HVBATT	High Voltage Battery
HVDC	High Voltage Direct Current
IFSD	In Flight Shut Down
MG	Motor Generator
MGB	Main Gearbox
PDS	Power Distribution System
PE	Power Electronics
TSHAFT	Turboshaft

Sign Convention:

TQ > 0	The engine supplies mechanical power to the MGB (motor driving condition)
TQ < 0	The engine draws mechanical power from the MGB and supplies (electrical) power back to its source (generator condition)

2 INTRODUCTION

For more than 60 years, turboshaft engines supply mechanical power to main gearboxes to enable the rotor to provide lift and propulsion to the helicopter. From the very first turbine engines, Turbomeca and then Safran realized that the accurate control of the supplied power was just as important as the knowledge of the bare engine. The same care is now given to control hybrid electric powerplants, so as to draw the very best in each engine technology to enhance the helicopter’s safety and operational performance.

The concept outlined here consists of integrating an electrical machine supplied by a high power battery, connected to the main gearbox in parallel of the turboshaft (see Figure 1). This electrical engine is primarily used to provide some backup power to the helicopter rotor in case of any major failure of the turboshaft. However, the current state of the art of rechargeable electrochemical batteries makes the power and energy sizing points greatly dependent on each other. Then, the maximum power required by the aircraft for the emergency manoeuver leads to a battery sizing that could offer some extra energy compared to the amount needed for the alternate flight and landing. The battery could also be voluntary sized to offer enhanced operational performances.

Thanks to the available extra energy, the electrical engine can also assist the main turboshaft in nominal daily conditions (without failure) by simultaneously providing or withdrawing power to/from the main gearbox. The hybrid propulsion control system can use the electrical engine to seek operational and environmental objectives such that:

1. Reducing the engine wearing by shaving the large power excursions
2. Reducing the local exhaust gaz emissions by using some part of carbon-free energy stored in the electrical battery

This nominal operation uses the battery as an energy buffer, occasionally drawing power from it and recharging it in other appropriate operating phases, while preserving at all times the energy reserve required for the emergency manoeuver. In this case study, the power and energy available from the electrical drivetrain is still low compared to those of the thermal drivetrain. Then the turboshaft still provides most of the propulsion power and over 95% of the energy required for the flight.

The hybrid nature of this concept means that heterogeneous power sources need to be cautiously integrated from a control perspective, to offer a safe and seamless propulsion system to the operators. The control architecture proposed here is designed such that both engines natively deal with nominal and failure conditions while ensuring the level of independence required by the safety considerations.

The control concept presented below is granted by the patent application FR3136131.

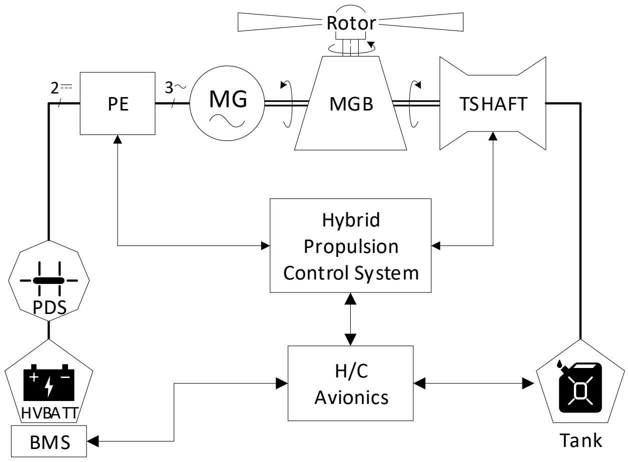

Figure 1 : Functional architecture of a parallel hybrid propulsion system

3 HYBRID POPRULSION ARCHITECTURE

This study focuses on a parallel hybrid-electric propulsion architecture dedicated to providing motive power to a helicopter (Figure 1). A turboshaft engine provides the main propulsion power to the H/C main gearbox through its drivetrain input. In parallel, the electromechanical drivetrain, composed of a reversible motor/generator rotating machine, its dedicated power and control electronics and a high voltage electrochemical battery, provides complementary or backup power to the H/C main gearbox. Both thermal and electrical engines are controlled by a hybrid propulsion control system whose role is to modulate the instantaneous power supplied by each engines to meet the H/C needs and to maintain the engine parameters within their sizing domain of operation. Finally, the H/C avionics assists the pilot in operating the helicopter, in monitoring the battery and fuel tank gages, and displays the critical parameters of both engines to the pilot.

Note that the architecture depicted hereabove is purely functional, it does not preclude the organic allocation of the functions. For safety considerations, control performance and industrial aspects, the breakdown of control units may vary from one application to another.

4 SYSTEM NEEDS AND CONSTRAINTS

On all helicopters the primary role of the propulsion system, either conventional or hybrid, is to provide the proper level of mechanical power, required by the helicopter main gearbox, in order to maintain the rotor speed NR, within some appropriate range. The hybrid electric system must also meet the following high level needs, and respects the mandatory constraints listed below:

1. For the safety of flight, in the potential event of a loss of power of the main turboshaft, the control shall always maintain an energy reserve in the battery during normal operation, sufficient to ensure a safe alternate flight and landing.
2. The control shall maintain the rotor speed within a safe range around its nominal setpoint, in all conditions including after a loss of power of the main turboshaft. For safety reasons, the rotor speed shall be maintained in its safe range whether the power loss is detected or not.
3. The control shall ensure a safe operation of the whole electrical powertrain. Hence, it shall keep the torque and the power or current of the electrical engine within min/max bounds given by the design. It shall also keep the HVDC bus voltage and the battery current within acceptable min/max limits to comply with the charging and discharing capacity of the battery.
4. The control shall ensure a safe operation of the turboshaft by keeping the engine parameters in their normal range of operation. These parameters are the torque of the power shaft, the gaz generator speed N1, the exhaust gaz temperature T45, and fuel flow limits preventing the engine from surging or flaming out.
5. The control shall minimize the wearing of the turboshaft by appropriately making the electrical engine contribute to the power supply. The wearing reduction is assumed to be achievable by maintaining some appropriate turboshaft parameters within least ageing limits.
6. The control shall limit the battery wearing by minimizing the cycling and by keeping the battery current in some low ageing limits.
7. The control shall allow the operator to reduce the flight pollutant emissions and the fuel consumption by enforcing a controlled discharge of the battery during the flight.
8. The control of the power sharing between the turboshaft and the electrical engine shall provide some seamless operation for the pilot. The power sharing variations shall not induce any significant variation of the rotor speed.

The hybrid propulsion control system may also consider additional objectives, such as the protection the drivetrain against overtorque, or preventing the electrical system equipment from overheating. This paper does not deal with these constraints but they can easily be handled in the same way as explained herein.

Since there are only two actuators (the thermal and the electrical engines) to handle over height objectives, not all objectives can be simultaneously met in all flight conditions. The system designer must define priorities between the objectives in order to handle the conflicting situations. For instance, it is mandatory to give the priority to safety constraints with respect to least critical operational objectives.

5 CONTROL DESIGN

A dedicated and new control function is developed to manage the power sharing between the turboshaft and the electrical engine, with the essential specification to meet the objectives and constraints listed in the previous paragraph.

As mentioned earlier, apart from the improbable power loss conditions, the turboshaft engine provides most of the power and energy required by the helicopter. On the other hand, the electrical engine can only assist the propulsion with limited power magnitude and time duration. Hence, in nominal conditions, the control of the rotor speed is kept allocated to the turboshaft, as on any conventional H/C powerplant. Accordingly, the electrical engine is dedicated to the control of the power sharing, in open loop with respect to NR. It is expected to autonomously take over the control on NR only in case of failure of the turboshaft leading to a lack of power.

The following paragraphs further detail de design of the electrical engine control which is intrinsically designed to handle both nominal and failure conditions. For the sake of conciseness and clarity, not all objectives are elaborated, but the general control principle and the design process is similar for all.

5.1 Control architecture

The management of the numerous concurrent objectives is fulfilled based on the following principles (see Figure 2):

1. First, we define N commands individually dedicated to each of the N objectives and

constraints to be met. The unified N commands are the torque orders the electrical machine has to deliver. This practical choice is relevant as the controller of the electrical machine easily treats the torque reference, by converting the datum into the motor/generator reference current for the standard current control loop.

In this way, a signed torque setpoint TQm_i^* is assigned to each objective Oi. Every objectives have their dedicated control function operating in parallel, independently from each other.

2. Then, all the individual torque commands TQm_i^* are combined by passing through selection gates such as min/max operators. The arrangement of these gates in relation to each other allows ordering the level of priority of each torque command TQm_i^*, to satisfy the prioritization of objectives defined by the system designer.

   At the end of the aggregation process of the torque commands TQm_i^*, a single torque setpoint TQm* is produced and sent to the electrical engine controller.

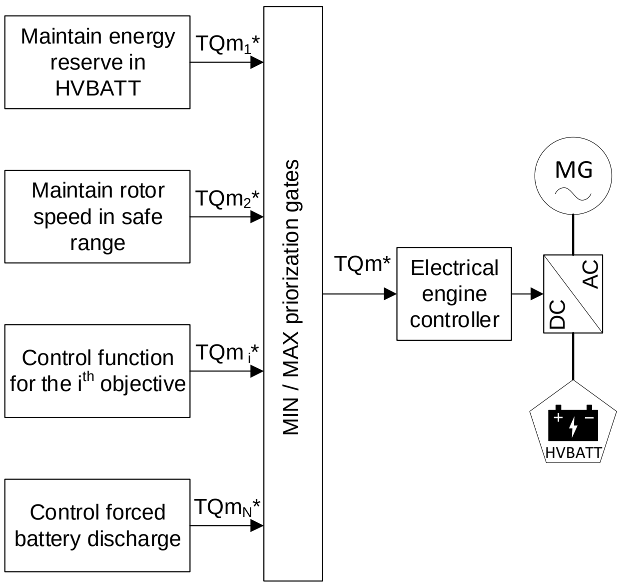

Figure 2 : Block diagram of the multi-objective control architecture. Only a few objectives are shown as a generic structure.

This control principle offers a great flexibility as the arrangement of priorities can be easily modified, by simply reordering the selection gates, with no impact on the control functions dedicated to each objective. Moreover, the high independence between these control functions allows designing and tuning them separately and having wide disparities in transient performances whatever the ordering of priorities.

5.2 Control of individual objectives

All the objectives and constraints are translated into a mathematical formulation which allows synthetizing the dedicated control laws. Depending on the control performances required from the hybrid propulsion system, the functions may be implemented as either open loop or closed loop control, including either linear or non-linear controllers.

When a closed loop control is required, the objective is to be converted into some setpoint to follow or a limit not to exceed, noted R_i^*, and a similar feedback parameter Y_i must be available (obtained either from a measuring sensor or by some indirect estimation). Finally, each controller can be designed by applying the standard control theory, resulting in the following generic control equation:

$$TQm_i^* = K_i \cdot (R_i^* - Y_i)$$

Where K_i is the controller transfer function.

As an example, the objective of maintaining the reserve of energy in the battery during normal operation is achieved by controlling the state of charge (SOC) of the battery. It is assumed the energy reserve can be expressed as a minimum limit of the battery state of charge SOCmin* and that an estimation of the current battery state of charge, SOCfbk, is available to the hybrid propulsion control system. A linear proportional-integral controller can be synthetized to command the appropriate torque command TQm^*_{SOCmin} that prevents the SOCfbk from decreasing below the limit SOCmin*.

6 TEST RESULTS

6.1 Test setup

Tests were carried out on SAFRAN's engine test rig, adapting it to incorporate the additional electrical powertrain, so resulting in a hybrid propulsion system test bench (see Figure 3).

The test setup includes the 600 kW class Arriel turboshaft engine, supplied with fuel by the testing facilities. In parallel of that, the electrical powertrain is composed of a 100 kW class electrical machine and its dedicated power electronics, supplied by a battery emulator. The latter consists in a reversible and regulated HVDC power supply, offering the capacity to simulate the behavior of a high voltage Li-ion type battery. For these tests, it was used essentially to simulate the simplified output impedance of a battery. The permanent magnet synchronous electrical machine and its power electronics are scaled-down lab prototypes which are fully representative of electrical engines embeddable on helicopters.

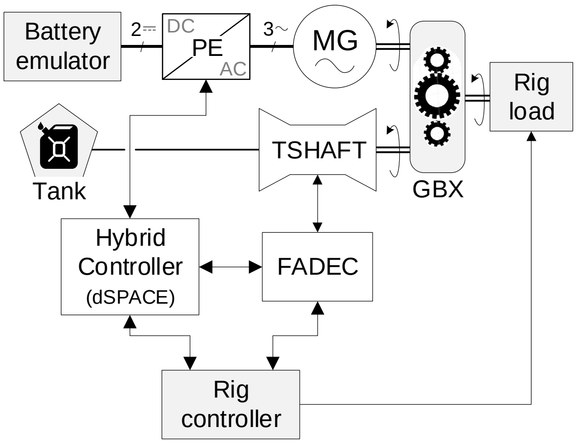

Figure 3 : Hybrid-electric engine test rig schematics

The Arriel turboshaft and the electrical motor/generator are connected to a gearbox (GBX) which sums the mechanical power of both engines and drives the rig load. This rig load includes a flying wheel and a Froude brake representing the load of the helicopter main rotor.

On the control side, the turboshaft is controlled by its Full Authority Digital Engine Controller (FADEC). A real-time rapid prototyping dSPACE® based platform was used to implement most of the hybridization control laws. This hybrid controller sends the signed torque command and receives some feedback data to/from the PE controller through a high-speed digital datalink. The FADEC software has been modified to host some hybridization functions requiring a close integration with the engine control. Thus, a datalink between the FADEC and the hybrid controller transmits preliminary torque commands toward the electrical engine.

Finally, the rig controller allows piloting the overall test, it controls the rig load in order to simulate various flight scenarios, and communicates with the FADEC and with the hybrid controller on behalf of the H/C avionics.

This test bench was used to validate both the control of the electrical powertrain and the power sharing control architecture presented hereabove. First, each control function dedicated to every objective has been individually tested and validated. The following two sections present some illustrating test results recorded on this test setup

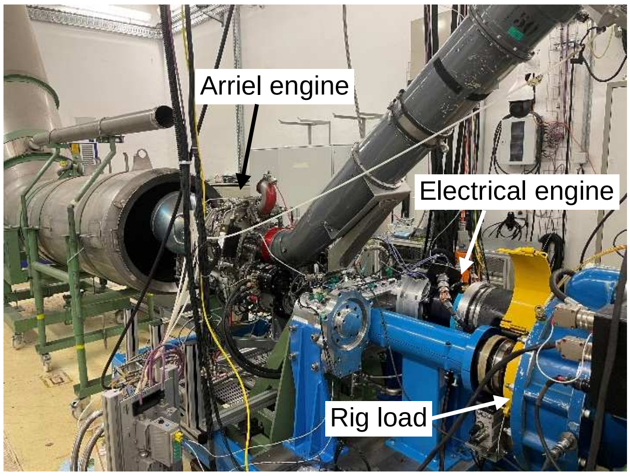

Figure 4: Picture of the hybrid-electric test bench

6.2 Maintain energy reserve in HVBATT

The validation of the SOC control loop of the battery, dedicated to the 1st safety objective listed in the §4 of this document, is shown here as an example.

For this partial integration test, the SOC limitation functions between the lower limit SOC^*_{min} and the upper limit SOC^*_{max} is tested alone. The Figure 5 illustrates the functional scope of this test. To test the limitation functions, the raw torque command TQm^*_{RAW} is manually set in open loop. It represents any engine torque command that could come from other objective control function whose priority is lower than the energy of the battery.

This raw command is upper bounded by the command TQm^*_{SOCmin}, produced by the SOCmin controller, and lower bounded by the command TQm^*_{SOCmax}, produced by the SOCmax controller. On this example, the SOCmax limitation has higher priority than the SOCmin limitation because the MAX selection gate is placed downstream the MIN gate. At the end, the final torque command TQm*, respecting the SOC limitation objectives, is sent to the power electronic controller to meter the power of the electrical machine. The actual torque on the MG shaft TQm is measured by the test bench instrumentation but is not used by the control. It is simply plotted to show the physical result of the power control.

The Figure 6 plots the electrical engine torque commands (bottom graph) and the resulting battery SOC (top graph) recorded on the test rig. Ones can observe five remarkable phases on this record.

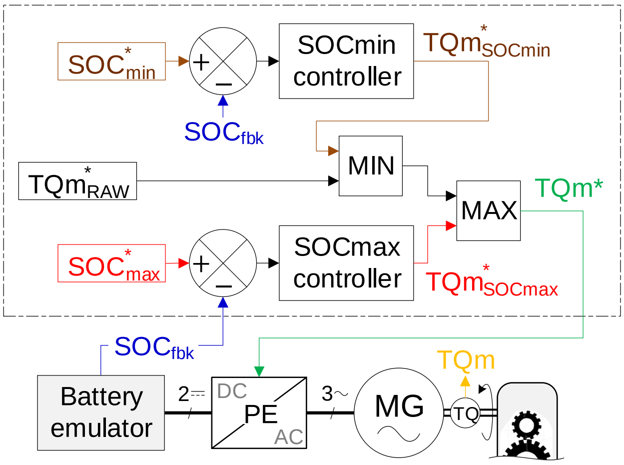

Figure 5: Simplified functional diagram of the SOC limitation control used for partial integration test. *The color code and label for variables matches the caption of the curves on Figure 6.*

Phase – 1 – The measured SOCfbk is well in between the lower and upper limits so both SOCmin and SOCmax controllers allow large excursions of the torque command between -80 Nm and +100 Nm. The raw torque command TQm^*_{RAW} is null so the final command TQm* matches the former one, leading the battery SOC to remain almost constant around 97%.

Phase – 2 – The raw torque command TQm^*_{RAW} is manually set to +100 Nm, leading the measured SOCfbk to decrease (cf. sign convention). During the first 10 s, the SOCfbk is still far enough from the lower SOCmin limit so the controller keeps allowing the final command TQm* to match the raw one.

Phase – 3 – Then, when the SOCfbk approaches the SOCmin limit, the controller starts lowering its TQm^*_{SOCmin} command, forcing TQm* to leave TQm^*_{RAW} and to progressively vanish. During the last 15 s of this phase, the SOCfbk is clamped on the SOCmin limit thanks to the TQm^*_{SOCmin} command which forces the torque to zero.

Phase – 4 – the raw torque command TQm^*_{RAW} is arbitrary set to -60 Nm, causing the MG to recharge the battery as shown by the increasing SOCfbk. All along this phase, the SOCfbk is far enough from the upper SOCmax limit to allow the raw command to be applied (the TQm^*_{SOCmax} command is maintained lower than the raw command, at -80 Nm).

Phase – 5 – Just before 150 s, as the SOCfbk approaches the SOCmax limit, the controller starts raising its TQm^*_{SOCmax} command until it reaches TQm^*_{RAW}, forcing TQm* to leave TQm^*_{RAW} and to progressively cancel. During the last 35 s, the torque command is forced to zero by the SOCmax controller, thus preventing the measured SOCfbk from exceeding the upper SOCmax limit.

Ones should notice that the power or current limitation of the battery was not taken into account at this intermediate integration stage. That's why the recharging power level shown on the Figure 6 is not representative of real battery limitations.

Every control functions were individually tested and validated by a similar process before testing the whole power sharing control system. The next section presents the results obtained with the fully integrated control on a particular failure scenario.

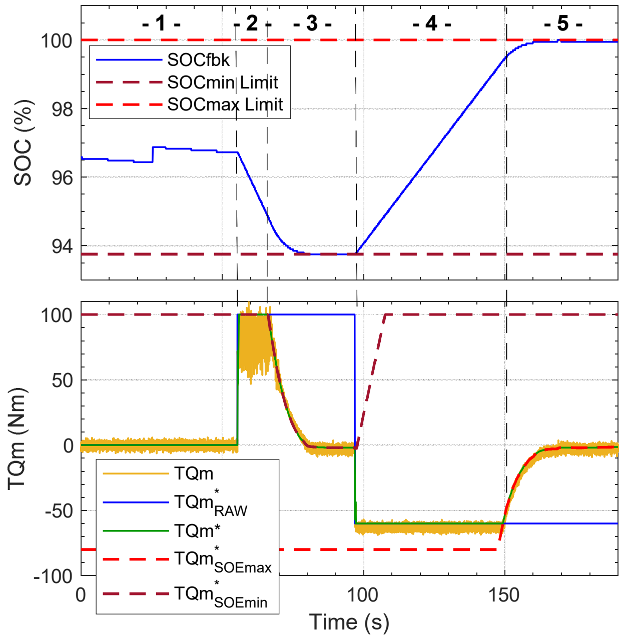

Figure 6: Example test results of SOC limitation between lower and upper limits on hybrid test bench. *Functional meaning of variables is shown on Figure* 5 *with the same color code.*

6.3 Power loss test

The Figure 7 hereafter presents a test scenario simulating an IFSD of the turboshaft engine during a low power flight phase. Because of the fairly low power capability of the electrical machine (100 kW), the test could only be carried out at a limited initial power level to enable the backup engine to hold the rotor speed NR.

Before the IFSD the turboshaft provides 100% of the propulsive power, operating at 230 kW (see purple curve on the bottom graph). The electrical MG runs at no load.

The IFSD is simulated by switching the turboshaft engine in an idle mode, providing no more power but still running. This is why the gaz generator speed N1 stabilizes a little above 60% and the free turbine speed N2 eventually desynchronizes from the NR but does not fully drops off.

When the IFSD occurs, the hybrid control system's NR protection function automatically commands the maximum power setpoint to the electrical engine (see turquoise colored curve on bottom graph), trying to recover the falling NR. However, the 100 kW power limitation of the electrical engine, lower than the power requested by the bench load (see blue and yellow curves on bottom graph), does not allow to maintain NR until the pilot releases a little the collective pitch (XPC) at approx. 438 s to reduce the load.

Then the power provided by the electrical motor allows slowly recovering NR (see green and blue curves on the top graph). Between 446 s and 458 s, ones can observe the decreasing MG raw power command as long as NR approaches its reference speed. It reflects the adaptation of the electrical engine control to measured NR changes. The power command converges toward the load power level drawn by the test bench. Unfortunately, the test was interrupted soon after NR reached its setpoint so the stabilization after the recovery is not visible.

During this test, the automatic takeover of the electrical engine is achieved by the same control principle as described above for the energy limitation. Hence, the activation and full power delivery of the alternate powerplant is obtained fully independently from the main engine control system, without relying on any explicit failure detection logic. A great advantage of this control method is that the NR speed control loop remains always active, running in the background while there is no failure, ready to takeover the control of the electrical engine, without requiring any tricky activation and initialization phase.

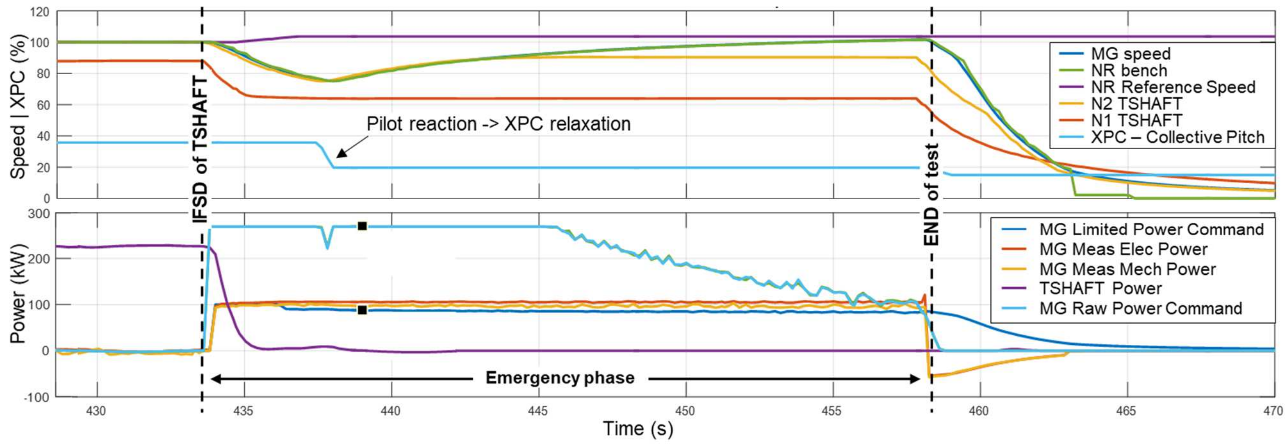

Figure 7: Example test results of the first emergency transient phase after a In-Flight-Shut-Down of the turboshaft

7 CONCLUSION

The present paper highlights the benefits of a parallel hybrid propulsion control system designed as a whole function to be fully integrated with both powertrains. This design inherently deals with any number of concurrent objectives and constraints of various criticality and transient timescales. It manages conflicts between objectives by explicitly ordering priorities in relation with the propulsion system designers. This control principle takes full advantage of each power source while minimizing the risks of adverse interaction.

The above control architecture and underlying control loops was tested and validated on a real parallel hybrid propulsion test bench in SAFRAN's facilities.

The work shown herein allowed SAFRAN to make a great progress in the control of parallel hybrid propulsion systems.

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