Layout and testing of a serial hybrid electric powertrain for a light twin demonstrator platform

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Abstract. The Project “RS hybrid 1.0” funded by the LuFo Program of the German BMWi is being executed in order to develop and investigate a serial hybrid electric powertrain to be used in a light twin aircraft, that could be exclusively operated on two electric motors. The powertrain includes a generator system, that provides energy to all power sinks like propulsors, batteries and also covers the low voltage demand of the aircraft. In the frame of this project, all necessary components are developed including the electric propulsion units, the hybrid generator system, battery modules, and DC-Link and associated subsystems. Everything is assembled in an iron bird testbed to be able to run the powertrain in an isolated fashion, to screen for potential issues and to measure operational data. Furthermore, a comprehensive control logic for the overall system and safety management of the powertrain is being developed and tested.

1. Introduction

The reduction of emissions has become a main challenge for modern day aviation. Hybrid Electric Propulsion Systems (HEPS) could be a viable solution for the field of general aviation [1]. In a serial HEPS, this is mainly done by decoupling the Internal Combustion Engine (ICE) from the propulsor, which no longer have coupled RPM ranges and allows for an ICE downsizing and also operation in the best economy point. Other possible benefits include the reduction of noise, an increase of safety and the lowering of operation costs. There are numerous analytical studies and concept aircraft [2], that investigate the benefits of the application of HEPS in existing conventional aircraft [3] and in purpose-made new designs [4]. However, there are not many applicatory studies that focus on the real-world implications of designing and operating such a system.

The disadvantages of a usually heavier and more complex propulsion system have to be outweighed by the possible advantages in the design. As concluded in [5], light aircraft have a wider variation of power required for different flight conditions compared to large aircraft. This can be exploited for reducing the overall fuel consumption for a given mission with a hybrid powertrain by using a thermal combustion engine in its operation point with the lowest specific fuel consumption. Excess power can be stored in a battery which can be used to provide electric power during phases of high power demand.

Additionally, a serial hybrid electric system has the potential to be operated on batteries alone, which might be desirable for noise emissions especially during flight phases close to the ground or even necessary if the targeted flight profile requires a silent mission segment.
2. Target flying platforms

2.1. SK 202
The former RS-UAS GmbH developed a low power demand and high-flying platform for research and reconnaissance purposes. This aircraft in motor glider configuration with 20m span and 2.5t MTOM was designed to be either piloted or operated autonomously. This aircraft is an ideal platform for a serial HEPS application with its centralized engine bay and optional hardpoints on the wing for additional motors beyond the main propeller in the centreline of the aircraft.

Unfortunately, economic factors led to the cancellation of the development of this platform and it was no longer available as demonstrator platform.

![Figure 1. RS-UAS SK202 [credit: RS-UAS GmbH]](image)

2.2. APUS i2
During the project, another very suitable target platform emerged as an alternative for a first application of the HEPS in development. The APUS i2 is a 4-seat light twin, with two electric propulsors and a firewall forward engine bay available as installation space. The final aircraft will be powered by hydrogen fuel cells that will provide the necessary electric energy to drive the motors during cruise. The Diesel-electric generator system developed in the project is therefore only used to test the overall architecture as well as the individual electric components.

![Figure 2. APUS i2 [credit: APUS Aero Engineering GmbH]](image)
3. Powertrain architecture

![Figure 3. Simplified HEPS architecture](image)

3.1. System description

The propulsion system being tested is a serial hybrid electric powertrain with two propulsors and a high voltage power/energy supply. The system is designed with two symmetric branches for redundancy aspects in which the two sides can be isolated from each other in case of a critical malfunction using the crossfeed functionality. In case of a minor malfunction, a single component can be electrically cut off and both sides of the power supply can feed one propulsor or vice versa. This way, the flight can be terminated safely. In normal operation, the power is distributed evenly for minimum load on the respective components.

The system operates at a nominal voltage of 400 V. For the used power range this poses a good compromise between keeping the weight of the cables low while minimizing the effort that has to be taken to isolate the components.

3.2. Major components

The main components of the powertrain, as shown in Figure 3 and are listed below in Table 1 with their mass, their maximum continuous power (MCP) and their efficiency. In the following sections, a more detailed look is given on the ICE, the generator and the associated inverters, the batteries and the electric motors.

| Component          | Mass     | MCP      | efficiency |
|--------------------|----------|----------|------------|
| Generator SP170G   | 24.4 kg  | 130 kW   | 95%        |
| Generator Inverter | 2x 9.8 kg| 2x 120 kW| 98%        |
| Batteries          | 2x 65 kg | 2x 65 kW | 95%        |
| Electric Motors    | 2x 20.3 kg | 2x 65 kW | 95%        |
| Motor Inverters    | 2x 6.7 kg | 2x 160 kW | 95%       |
| DC/DC converters   | 2x 5 kg  | 2x 1.5 kW | 94%       |
| ICE CD155          | 128 kg   | 114 kW   | 214 g/kWh |
3.2.1. Internal combustion engine. The necessary power during cruise flight is provided by the Diesel engine CD155 by Continental Motors. The choice to use a Diesel-cycle engine rather than a more conventional aircraft engine, was made early on in the development of the SK202 for which the powertrain was originally designed. During the long flight time with low power settings, the better efficiency is an advantage that outweighs the additional weight of the Diesel engine.

Several engines from different manufacturers were considered, but only two were chosen for a more in-depth analysis. The Danielson Trident 100, which provides 75 kW, and the Continental CD155, which provides 114 kW. For both engines the fuel consumption during a typical mission was calculated and added to the base weight of the engine. These calculations were done for the stock engine as well as for a version optimized for the use in a generator system, where the fuel consumption was reduced through technical measures by the manufacturers. As a reference, a state-of-the-art gasoline engine, the Rotax 915iS, was also included in the studies. The results are shown in Table 2 below. They prove, that the assumption made at the beginning of the project was correct, as the gasoline engine has the highest overall system mass, caused by the significantly higher fuel burn. According to the calculations, the best option is an optimized version of the Danielson Trident 100, as the low mass of the engine would make up for the higher fuel consumption compared to the Continental CD155.

|                  | Rotax 915iS | Continental CD155 | Continental CD155 | Danielson Trident 100 stock | Danielson Trident 100 opt |
|------------------|-------------|-------------------|-------------------|-----------------------------|--------------------------|
| peak efficiency  | 270         | 216               | 205               | 233                         | 215                      |
| Mass fuel [kg]   | 425         | 343               | 323               | 367                         | 340                      |
| Mass engine [kg] | 77          | 130               | 130               | 72                          | 72                       |
| Total [kg]       | 502         | 473               | 453               | 439                         | 412                      |

Despite the results of this calculation, the final choice still fell on the CD155. A main reason for that is the better performance at high altitudes of the turbocharged CD155 compared to the naturally aspirated Trident 100.

3.2.2. Electric motors.

For the electric motors, two Emrax 268 MV were used (see figure 4). The 268 MV is an axial flux, permanent magnet synchronous motor, designed as an outrunner machine. It is optimised to provide high torque and can deliver the necessary power for the propellers without the use of a gearbox, thus saving weight. It has a very good power to weight ratio and also an integrated propeller bearing which makes it possible to mount the propeller directly on the motor. The high power density requires an adequate cooling system, which is accomplished by using a dual (air/liquid) cooling layout. Both motors are equipped with an encoder position sensor and combined with suitable inverters to the so-called Electric Propulsion Units (EPU).
3.2.3. **Batteries.** To boost the power during take-off and as a backup in case of a failure of the ICE, high power batteries are needed. Since there are no readily available aircraft batteries in this category on the market, they were designed and built in-house using state-of-the-art Li-Ion cells.

Each battery provides at least 65 kW of continuous power depending on State of Charge (SOC) and can store 10.5 kWh of electric energy. It consists of 1080 cylindrical 18650 Li-Ion cells. To form a battery sub-pack, each ten of these cells are welded together in parallel, using thin pieces of copper sheet metal. Those sub-packs are each equipped with a slave module, that measures voltage and temperature of the unit and transfers this data to the Battery Management System (BMS), where it is interpreted and made available through a CAN-Bus. The cell packages are then stacked together to form the battery pack. The path from a single cell to the whole battery pack is shown in Figure 5.

![Figure 5. Construction of a battery from a single cell (top left) to the finished battery pack](image)

As the power demand during take-off is high but only lasts for a short time, the emphasis during the design was put on a high specific power rather than high specific energy. The high power provided during take-off makes it necessary to implement an effective cooling to keep the cells within the safe temperature range. To reduce potential sources of failure, it was decided to use air to cool the batteries rather than a more complex and heavy water cooling. This is done by integrated air channels in the structural elements of the housing. As shown in Figure 6, cold air flows in from one side and gets evenly distributed beneath the cells. It rises through the cell packages absorbing heat on its way before being sucked out by fans on the side of the battery.

![Figure 6. Cooling concept of the battery](image)
3.2.4. Generator. The generator, a Rolls Royce SP170G, originally developed by Siemens, is directly coupled to the engine. It is a permanent magnet synchronous machine with a MCP of 130 kW. The outer stator is bolted to the engine housing, while the inner rotor is connected to the crankshaft. There is no main bearing needed, as the gap between rotor and stator is secured by concentric installation. This reduces the number of individual parts and improves reliability. Another notable feature of this electric machine are the double windings in the AC output. In case of a failure in one of the halves, the generator is still able to run on half its power, thus enabling the aircraft to fly safely to the next airport.

3.2.5. Generator Inverter. The generator inverter is 4-quadrant electric power converter that has been configured to be used with this electric machine. The hardware as well as the software have several safety features that make them suitable for aerospace applications.

The device can be used without position/speed sensor through sophisticated software, which makes it impossible to fail due to a sensor malfunction, interrupted wire or electromagnetic interference (EMI).

There are two units being used, to respect the redundancy aspects of the generator with dual windings.

4. Control
The control and safety management of the whole HEPS is done on a Programmable Logic Controller (PLC) which is called Hybrid Control Unit (HCU) in the following.

Because of the custom design of the prototype, the software running on the HCU is a clean sheet design developed during the project.

The HCU is the central controller with numerous digital and analog I/Os for the control and monitoring of the power distribution of all main components, the speed control and their ramp rates. Additionally, it controls secondary functions like electrical high voltage contacting, precharge functionality, cooling and fuel pump control, DC/DC control and initializing of components where needed.

For the operation control, a finite state machine is implemented to make sure all of the different modes are mapped correctly and make the hot transition during live operation smooth with no handover errors from one mode to the other. Operation modes include predefined settings, maximum available power, pilot defined power, source-sink-parity, etc.
4.1. Efficiency implementation

Another possibility for the HCU is the evaluation of the efficiency of the system. In case of the electric propulsors, this efficiency can be defined as the combination of the electric machine, its power regulator and all purely resistive losses in the wiring. In case of the ICE-generator combination (GenSet), the additional thermal efficiency of the ICE would have to be included. For the latter case, the PLC evaluates the power input in form of fuel and the rectified electric power fed to the DC-Link

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \]

The input power \( P_{\text{in}} \) is determined by

\[ P_{\text{in}} = H_{\text{Diesel}} \cdot \dot{V}_{\text{Diesel}} \cdot \rho_{\text{Diesel}}(T_{\text{Diesel}}) \]

as well as the empiric relationship of temperature on the density of the fuel in [g/L].

\[ \rho_{\text{Diesel}}(T_{\text{Diesel}}) = 1008,86 \frac{kg}{m^3} - 0,6335 \frac{kg}{m^3 K} \cdot T_{\text{Diesel}} \]

The converted power is integrated by counting the generated and rectified energy in the chosen time interval,

\[ P_{\text{out}} = U_{\text{DC}} \cdot I_{\text{GenSet}} = \frac{1}{T} \int_{t_1}^{t_2} p(t) \, dt = \Delta E_{\text{el}} \]

And yields the combined efficiency over all components of this HEPS branch for any time interval

\[ \eta_{\text{comb}} = \frac{\Delta E_{\text{el}}}{\Delta t \cdot H_{\text{Diesel}} \cdot \dot{V}_{\text{Diesel}} \cdot \rho_{\text{Diesel}}(T_{\text{Diesel}})} \]

This efficiency metric can be used for a parameter based optimizing function in an operation mode that uses a feedback loop control to find the best fuel burn globally or for a specific power output.

4.2. Safety measures

To be consistent with the strictly redundant main components, the communication was also isolated in left and right branches. As communication system, a fully digital system was chosen, using a CAN bus. The reason for this choice was that the bus is very robust against noise and allows the simple exchange of components at a later time if necessary.

All critical parameters like temperatures, rotational speeds, pressures, voltages, amperages are monitored by the HCU and the respective limits defined to give warnings and/or automatically passivates the system to a safe state, depending on the severity of the fault. The implemented safety functions also include interlock monitoring and timeout events of digital data communication.

The PLC itself performs self-monitoring via its watchdog functionality and disables all channels in case of a malfunction. A second PLC with the same functionality could be introduced to be able to monitor both devices independently, but would require extensive changes in code.

The HCU also controls and initializes the Isolation Monitoring Device (IMD). All measurements of the IMD are transmitted to the HCU and processed for the GUI and the safety functions. With compromised isolation in one branch of the system, it is potentially hazardous to the rest of the aircraft and to humans, so it has to be switched off unconditionally.

Another safety function of the dual FADEC for the Generator ICE is the health monitoring of both halves of the FADEC. This is passed on to the HCU and processed. The side with the higher health value is engaged. This can be externally overwritten by the pilot in case of a malfunction.

Lastly, the HCU also protects the battery from excessive load and temperatures, as it is a passive system with no protection of itself.
5. Preliminary Experimental Data

![Graph showing data](image)

**Figure 8.** Propulsion system HV-data on exemplary simulated flight mission on iron bird

Preliminary test runs with the fully operational iron bird have been done. Figure 8 shows a simulated test flight which is divided into various sections as follows:

|   | Description                                                                 |
|---|-----------------------------------------------------------------------------|
| 1 | Brief phase of Take-off-power followed by a phase with cont. climb power, mostly battery based |
| 2 | Cruise power with very little generator support, battery draining            |
| 3 | Cruise power with generator power matching, battery idle                     |
| 4 | Slowly increasing generator power, battery is progressively recharged        |
| 5 | Sudden drop of generator power, battery is still recharged with a minor charge rate |
| 6 | Descent phase, Low power consumption, generator power is adjusted           |
| 7 | Go-Around with T/O-power followed by climb out, generator support is gradually increased |
| 8 | Cruise and return to approach, low charge rate                              |
| 9 | Landing and taxi, low charge rate to reach desired battery SOC for next flight |

The data shows a pronounced voltage drop on high load intervals due to internal resistance and a rise on being charged. This is expected and these characteristics will have to be considered for the implementation in the aircraft to determine and respect all battery voltage limits. Furthermore, the data shows us the dynamic responses of all power electronics to sudden control inputs. Step responses proved to be acceptable throughout the tested scenarios.

The system collects much more data like thermal and mechanical measurements. These are being used respectively to find weak points in the cooling systems or allow for fine tuning of the ground adjustable pitch of the propellers to optimize motor speeds.

All systems seem to operate as expected during these first test runs, but there needs to be more test effort to find potential error sources, test the system control algorithm for bugs, increase power on all components up to the specified limits and get information on the endurance and life cycle characteristics of the whole system.
6. Conclusion and Outlook
A twin electric engine hybrid electric powertrain was developed, designed, built up and put into initial operation on an Iron Bird test bed. The system is described in detail, the choices are explained and specifications are given.

The System consists of two independent halves to feature redundancy benefits and also has the option to couple these two halves and to operate them as one whole system. The benefits of the electrification include better overall efficiency, potential for slower propeller speeds, lower noise emissions during electric operation, potentially lower DOCs, much more design freedom when implementing the fully digital flight control and a considerably simplified transfer to an optionally piloted aircraft. Additionally, the power generating part can be easily swapped out for a hydrogen fuel cell at a later stage.

Disadvantages compared to a conventional twin are the higher complexity, increased weight, less historical experience, as in any research approach and more individual small-scale conversion losses throughout the system that have to be offset by the higher overall efficiency.

This very practical approach has been tremendously helpful in understanding the implications and interactions of a complex powertrain considering the general safety. Also, the best practices and certification rules for CS23 aircraft have been considered and help to integrate a slightly modified version of the powertrain architecture in an airworthy prototype.

The work includes the combination of COTS and self-developed components to a ground test setup. This will allow the extensive experimental validation in the whole conceivable operation range and the forcing of likely faults. After that, the goal is to run simulated flight missions to collect data and compare the hybrid electric system to conventional concepts used today. The main focus during the work was the development of an executable algorithm for managing the whole powertrain considering all the above.

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References
[1] Sziroczak D, Jankovics I, Gal I, Rohacs D. 2020 Conceptual design of small aircraft with hybrid-electric propulsion systems. Energy, Volume 204
[2] ICAO. 2019 Electric, Hybrid, and Hydrogen Aircraft – State of Play. Environmental Reports 2019
[3] Glassock R, Galea M, Williams W, Glesk T. 2017 Hybrid Electric Aircraft Propulsion Case Study for Skydiving Mission. Aerospace. 4(3):45.
[4] Bravo GM, Praliyev N, Veress A. 2021 Performance analysis of hybrid electric and distributed propulsion system applied on a light aircraft. Energy, Volume 214
[5] Donateo T, Totaro R, Spedicato L, Ficarelli 2017 Real World Fuel Consumption of a Piston-Prop Aircraft 7th EASN Conference