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Switching Logic for a Direct Hybrid Electric Powertrain

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Abstract: Hybrid electric aircraft with a powertrain based on fuel cells and batteries can reduce climate-active emissions in aviation. In a direct hybrid powertrain, the fuel cell and the battery are connected in parallel, without a DC/DC converter balancing their voltage levels. Switches make it possible to select different operational modes (fuel cell only, hybrid or battery charging) depending on the power demand during different flight phases. To exploit the high specific energy of hydrogen, the system should change from Hybrid Mode during take-off to Fuel Cell Mode in cruise. During descent, the battery can be charged if Charging Mode is selected. To avoid voltage and current peaks and consequent damage to components when switching between modes, certain conditions must be fulfilled. Those switching conditions were defined, and switching procedures for changing from one mode to the other during flight were developed and tested in a lab system. In a direct hybrid, the system voltage depends on the required power. When switching from Hybrid Mode to Fuel Cell Mode, a short reduction in power of 65% is necessary for the examined system to meet the switching requirements. It is also shown how this power loss can be reduced to 25% by distributed propulsion with a second powertrain or even eliminated by a change in the hybrid ratio.

Keywords: direct hybrid; fuel cell; battery; electric aircraft; switching logic

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1. Introduction

The aviation industry is rapidly expanding. Predictions suggest that the number of passengers will triple between 2020 and 2050 [1]. The use of conventional aviation fuels leads to a significant emission of climate-active gases such as CO_2, NO_x, unburned hydrocarbons and particles [2]. Those exhaust gases have a negative impact on the environment and enhance global warming [3–5]. To reduce the climate impact of aviation, new technologies, such as electric aircraft with no or at least with lower emissions, are needed [6,7]. This causes new challenges to emerge in aviation. Battery-powered planes are limited in their flight range due to the low specific energy of batteries. The use of hydrogen as an aviation fuel enables travel over longer distances and is seen as promising for intermediate-distance travel [8]. If hydrogen is converted in fuel cells, the only emission is water vapor [6,7]. In this context, the tradeoff between the low volumetric energy density of hydrogen of 600 kWh/m^3 at 200 bar [9] and the high gravimetric energy density of 33 kWh/kg [10] is well known and subject to developments in the field of hydrogen storage systems [11,12].

The combination of a hydrogen fuel cell and a battery in a hybrid electric propulsion system is seen as a promising concept for short- to medium-range flights [13–16]. The hybridization of the fuel cell and the battery enables combining the advantages of both technologies and a demand-oriented approach to provide the power required for propulsion in the best possible way [17]. The power demand during an all-electric flight depends on the flight phase like take-off, cruise and descent, just as in conventional aircraft. The exact values differ in comparison to conventional aircraft due to the different weight and design of an all-electric aircraft. Figure 1 shows a simple schematic of the associated power consumption during a flight profile [14] over time. The profile is based on flight data from the Hy4. During take-off and climb, the highest power is required for the aircraft to gain altitude. Once cruising altitude is reached, less than half of the power is required for level flight. The power demand decreases further during descent and the fuel cell can recharge the battery during cruise and descent when less power is required for propulsion than the fuel cell can supply. The powertrain has to be designed to always meet the required power demand in each flight phase. A powertrain powered exclusively from a fuel cell must be able to provide the power needed for the take-off and climb phase. As a consequence, the fuel cell is oversized for the cruise and descent phase. The battery provides additional power to the aircraft drive train during high-power-demanding phases, such as take-off. The fuel cell weight can therefore be reduced by using a battery. Fuel cell systems are also usually used in combination with at least a small battery to improve the dynamic performance of the drivetrain. A powertrain powered only from a battery that meets the given power requirements is very heavy and the low specific energy of batteries makes it unsuitable for longer flights [18].

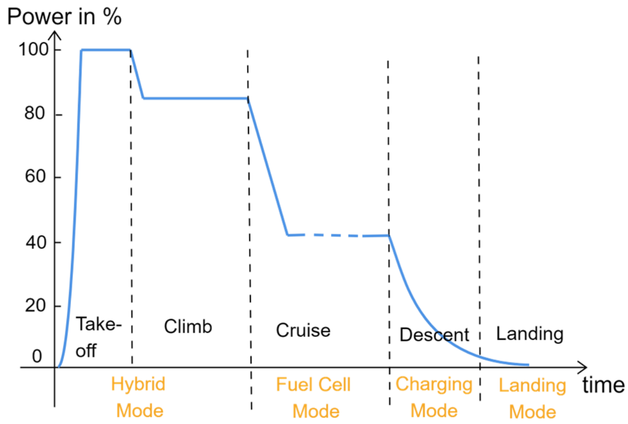

Figure 1. Schematic of a typical propulsion power demand profile with take-off, climb, cruise, descent and approach phases.

Different hybridization concepts exist, and the usual approach is the connection via a DC/DC converter. This approach is for instance used by Bhattacharya et al. [19] and Ng et al. [16], where the connection of the hybrid system is achieved via a DC/DC converter to adapt the voltage level. However, the use of a direct hybrid without DC/DC has advantages [20] even though this approach is not yet state of the art. Both Nishizawa et al. [21] and Hoenicke et al. [14] propose a direct hybrid system consisting of a fuel cell and a battery and point out the potential in the application in an electric aircraft. The architecture proposed by Hoenicke et al. [14] is a direct hybrid with an additional DC/DC for recharging the battery. Criteria for the suitability for aviation are safety/reliability, weight and efficiency. The power management proposed by Hoenicke et al. [14] achieves reliability through a redundant structure. Different from a DC/DC is the use of relays instead of semiconductor switches. The failures of the semiconductors (IGBT) are the main reason for failures in DC/DC [22–24]. In addition, the control circuit of a relay is simpler than that of a semiconductor switch [14]. The efficiency achieved by Hoenicke et al. [14] was above 99% during cruise and take-off which is higher than the usual efficiencies of DC/DC, which usually has efficiencies somewhere between 85% and 98%. Graf et al. examine the influence of the battery SOC [25] and the influence of the low ambient pressure [26] at high altitudes on the direct hybrid system and the resulting implications for dimensioning of a fuel cell and a battery [27] is investigated. A power unit combining a fuel cell and a battery in a direct hybrid can be used flexibly with the help of a power management system (PMS) as proposed by Hoenicke et al. [14] and already used in the previously described test-airplane HY4 [28]. Using the PMS, different operation modes can be chosen during flight according to the required power. During low-power phases, the fuel cell can power the aircraft alone, while the battery contributes to the power demand during high-power phases. In order to optimize the operation in a direct hybrid configuration, the operational mode has to be changed by the PMS during flight. A challenge in the dynamic operation is that it is not possible to switch from one operation mode to another operation mode at any desired moment; but when changing from one mode to the other, certain conditions have to be met to enable a smooth transition. Voltage or current peaks in the system must be avoided when switching to another mode, since they can potentially damage components, for example the switches themselves. This results in a set of voltage and current requirements for each transition that have to be fulfilled before switching. Since the voltage level of the fuel cell and the battery in a direct hybrid can only be changed by adjusting the motor power, this can lead to the necessity to decrease or increase power for changing modes during flight. This means that for the duration of the switching operation, the power provided is not guided by the demand, but by the switching conditions which might lead to unwanted decrease or increase propeller speed and torque.

In this paper, the switching conditions and resulting switching procedures and power adaptations for every mode change with respect to voltage and current requirements are defined and explained for the previously described direct hybrid powertrain architecture consisting of a fuel cell, a battery and a PMS [14]. The necessary power changes due to those switching conditions are examined and described for the most important mode changes when switching from Hybrid Mode to Fuel Cell Mode for the transition from take-off to cruise and from Fuel Cell Mode to Charging Mode for low-power phases during cruise or descent. During approach, another mode is required. When power is low, the airflow through the propeller can cause the motor inverter system to act as a generator, increasing the voltage in the system [29]. Despite the fact that recuperating energy from the propeller during that phase does not offer a great energy saving potential [30], the energy should be fed into the battery in order to avoid overvoltage which may lead to a shutdown and damage of the system [29].

The defined switching procedures for operation mode changes were implemented in the control of a previously described experimental setup [25] of a power train consisting of two DC sources representing the fuel cell and the battery, the power management system and a load. The results of the test and validation of the mode transitions with the switching procedures in the experimental setup are shown. After validating the required power adjustments in the laboratory, it is examined how the power reduction for switching from Hybrid Mode to Fuel Cell Mode can be reduced or avoided in a setup with two propulsion units and by modifying the fuel cell/battery ratio.

2. Materials and Methods

2.1. Direct Hybrid Powertrain of a Fuel Cell and a Battery

The most common hybridization method is to link the fuel cell and the battery with the help of one or even two DC/DC converters that adjust the voltage levels of both energy sources to the load voltage [16,19]. In a direct hybrid, however, the battery and the fuel cell are connected in parallel without a DC/DC converter that adapts the voltage levels [14,21]. Relinquishing the DC/DC can improve the systems reliability, power density, and efficiency [20]. Figure 2 shows a simplified schematic configuration of a direct hybrid power train, consisting of a fuel cell and a battery, as well as an inverter and a motor system. A power management system as proposed by Hoenicke et al. [14] connects the fuel cell and the battery to the motor/inverter system.

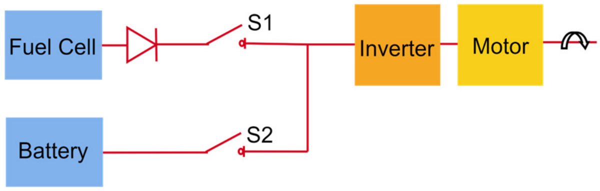

Figure 2. Simplified schematic of the direct hybrid powertrain consisting of a fuel cell, battery, power management system, inverter and motor.

The current–voltage behavior of the direct hybrid depends on the characteristic voltage–power curves of the fuel cell and the battery, as shown schematically in Figure 3. The fuel cell curve (in blue) depends not only on physical conditions, such as cell or stack size, but also on operational conditions, like operating temperature and pressure [26,31]. The same applies to the battery curve (yellow in Figure 3) which is dependent on physical conditions such as number of cells, the state of charge (SOC), state of health (SOH) and operational conditions such as temperature or the C rate [32]. It can be seen in Figure 3 that the slopes of the characteristic curves of the fuel cell and the battery differ. The slope of the battery curve is less strong than that of the fuel cell. For a direct hybrid, the open circuit voltage (OCV) of the battery must lie below that of the fuel cell. When the fuel cell and the battery are connected in parallel without a DC/DC converter, the resulting hybrid curve is a combination of the fuel cell curve and the battery curve as shown in red in Figure 3.

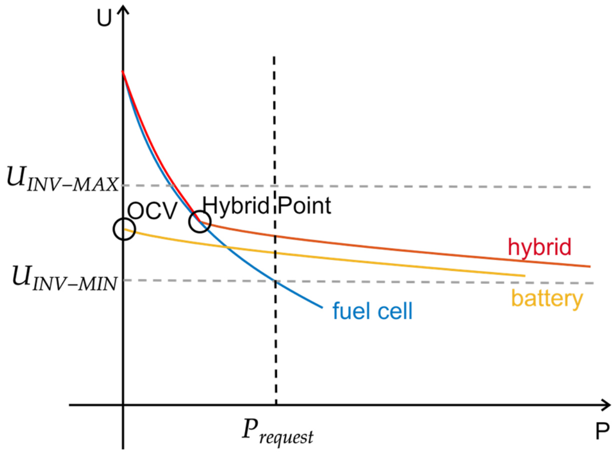

Figure 3. Schematic voltage–power characteristic curves of the fuel cell, the battery and the direct hybrid system [33].

When the fuel cell voltage reaches values below the OCV of the battery, the power is generated by both the fuel cell and the battery, resulting in the combined characteristic curve shown by the red line Figure 3. The point where the fuel cell voltage equals the battery OCV ($V_{FC}(P) = V_{Bat}\ (0)$) is called the hybrid point. In addition to the characteristic curves of the fuel cell and the battery, the limits of the inverter $U_{\text{inv-max}}$ and $U_{\text{inv-min}}$ are schematically plotted in Figure 3. Since inverters work within a given voltage range, these limits must also be considered when operating the combined system and when switching between modes. $P_{request}$ in Figure 3 represents the power requirement of the power train at a certain time during the flight, for example, during take-off.

In order to choose whether the power is provided by the fuel cell, the battery or the combined hybrid system, the PMS is required to select the power source for each flight phase. The power during the cruise phase should be completely covered by the fuel cell to enable a longer flight range due to the high specific energy of hydrogen. For the take-off and climb phases, which require a higher power, the battery can provide additional power for a short period of time. In the descent and approach phases (sometimes also during cruise), less power is required from the system, which means a surplus of energy is available and the battery can even be charged from the fuel cell. Recharging the battery during flight is important in the event of complications during landing and a repeated take-off, which is only possible if the battery state of charge (SOC) is sufficiently high. With the help of the power management system and an intelligent switching logic for it, different modes (fuel cell, battery, hybrid, charging, landing) can be used in different flight phases. This enables the fuel cell and the battery to be dimensioned according to the required power in each flight phase and reduces the weight of the system as much as possible [27].

Within the PMS, switches and diodes are used as shown in Figure 4 in order to select and choose between the different modes. Relays are used as switches since they offer low conduction losses and therefore a high efficiency. Their characteristic to handle overloads and the secure electrical insulation between the low voltage control and the high voltage connection make relays applicable for aviation. Diodes are used in the PMS to control the direction of the current flow. The fuel cell is safeguarded from reverse current by the inclusion of diode D1 in Figure 4. The battery connection has two diodes, D2 and D3, to ensure that the operating parameters for charging and discharging are not compromised.

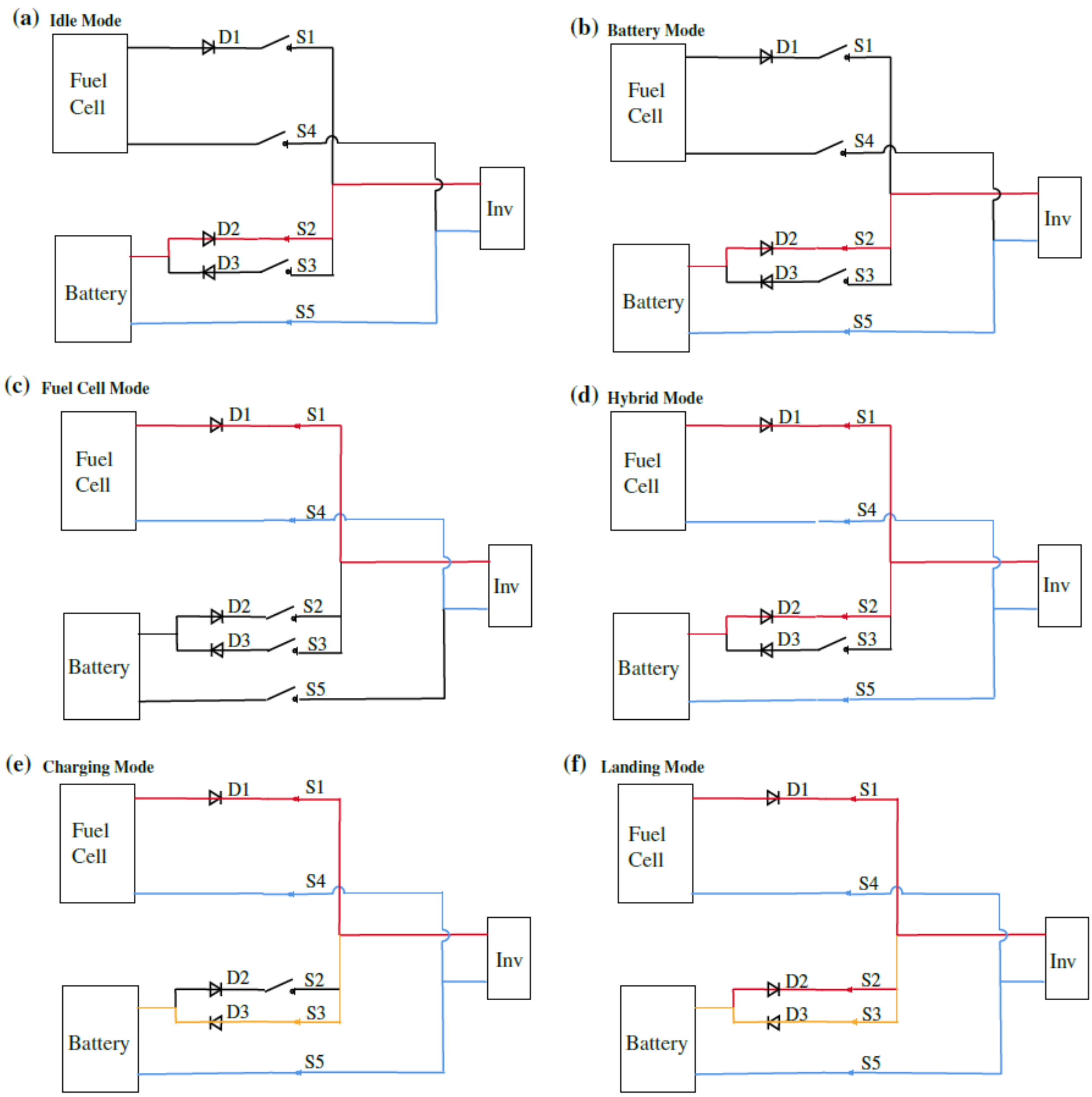

Figure 4. Switch positions of the different PMS modes: (**a**) Idle Mode. (**b**) Battery Mode. (**c**) Fuel Cell Mode. (**d**) Hybrid Mode. (**e**) Charging Mode. (**f**) Landing Mode.

S1 connects the fuel cell and S2 connects the battery to the inverter/motor system. S3 is used for charging the battery. The PMS as shown in Figure 4 enables the aircraft's propulsion unit to operate in the following modes [14]:

- In Idle Mode, all switches are open (Figure 4a). This is the situation before starting the system. In this mode, all sub-systems, the 24 V supplies of the components, the communication and the cooling of the system can be checked and tested before starting up.

- Fuel Cell Mode is the mode that is used for the longest duration during a flight. For a correctly dimensioned fuel cell, this mode delivers the required power during the cruise phase. The power flow in Fuel Cell Mode is shown in Figure 4c and it can be seen that switches S1 on the positive path (red line) and S4 on the negative path (blue line) are closed [14].
- Hybrid Mode is the mode of choice for take-off and climb phases that require the most power. If the power required by the motor for propulsion exceeds the power output of the fuel cell, the battery can provide additional power for a certain period of time. In Hybrid Mode, switches S1 and S2 on the positive path (red line) and S4 and S5 on the negative path (blue line) are closed [14], enabling a power flow as shown in Figure 4d.
- Battery Mode is not meant to occur during normal operation. It is, however, exclusively dedicated for emergencies situations. In case the fuel cell fails, the battery can supply power on its own for a certain period of time. In this mode, only the battery is connected to the inverter via switches S2 in the positive path (red line) and S4 in the negative path (blue line). The resulting power flow in Battery Mode is shown in Figure 4b.
- Charging Mode can be used in the descent phase, when the fuel cell can provide more power than the motor requires. This additional power can be used to charge the battery if the DC bus voltage generated by the fuel cell is higher than the battery voltage and the battery is not already fully charged (SOC < 100%). The charging path from the fuel cell is shown as a red and yellow line in Figure 4e. In Charging Mode, switches S1 and S4 are closed and current can flow from the fuel cell to the battery by switch S3.
- Landing Mode is required during approach and landing. To enable a go-around in case of an aborted landing attempt, the fuel cell as well as the battery have to be connected. At the same time, energy that is recuperated from the motor/generator has to be able to flow into the battery. Therefore, all switches (S1 to S5) are closed in this mode.

2.2. Mode Transitions in a Direct Hybrid Powertrain

In order to cover the different flight phases as efficiently as possible with a direct hybrid system of a fuel cell and a battery, the mode must be changed during a flight. During take-off and climb, the power demand is high and the system has to operate in Hybrid Mode. After the take-off and climb phase, the powertrain can be changed from Hybrid Mode to Fuel Cell Mode. This means that the battery is no longer used, and the cruise phase can be powered exclusively by the fuel cell. Towards the end of the flight (during cruise or during descent), the required power of the system is so low that the fuel cell can charge the battery in addition to providing the propulsive power. Therefore, the system must be switched from Fuel Cell Mode to Charging Mode. For approach and landing, the system should be in Landing Mode. Before switching from mode to mode, the control unit has to make sure that certain conditions are met. The control has to ensure that no voltage, current or power limits are exceeded and no unstable operating conditions occur. The control unit also has to make sure that there is no current flow through the relays and that there is no voltage difference between both contacts of the relay while opening or closing them. This last requirement arises from the fact that when switching relays under load, unwanted current or voltage peaks can occur, which can damage other components in the system (inverter, fuel cell, battery) or the relays themselves. When relays are opened or closed under load, electric arcs can occur between the contact points of the relay. As the voltage and current amplitude increase, the arc increases. Each arc can lead to loss of contact and/or deformation of the contact points. Repetitive use of relays under load for multiple cycles decreases their lifespan [34,35] and contact welding can occur if the voltage and/or current in the relay is too high [36]. In an emergency, the longevity of the relays is not a concern, but, whenever feasible, the power management system should refrain from switching the relays while under load.

Table 1 shows the conditions that must be fulfilled when switching from one mode to another. In order to go from Idle Mode to any other mode, the torque of the motor and thus the power must be zero. The same applies when switching from any other mode to Idle Mode. The aircraft should not be flying in Battery Mode for extended periods of time. This mode is an emergency mode in case the fuel cell fails, the battery can supply the motor/inverter system with energy for a short time. In emergency situations, voltage drops and current peaks are tolerated when switching to Battery Mode.

Table 1. Switching conditions form Mode to Mode.

Actual Mode	Next Mode	Condition	
Fuel Cell Mode	Idle Mode	Torque = 0	
	Battery Mode	Emergency	
	Hybrid Mode	$V_{Bat} < V_{FC}$	
	Charging Mode	$V_{Bat} > V_{FC}$	
	Landing Mode	No direct transition possible Transition via Hybrid Mode or Charging Mode	
Hybrid Mode	Idle Mode	Torque = 0	
	Fuel Cell Mode	$V_{Bat} < V_{FC}$	$(I_{Bat} = 0)$
	Battery Mode	Emergency	
	Charging Mode	No direct transition possible Transition via Fuel Cell Mode or Landing Mode	
	Landing Mode	$V_{Bat/OCV} > V_{FC}$	$(I_{Bat} > 0)$
Charging Mode	Idle Mode	Torque = 0	
	Fuel Cell Mode	$V_{Bat} > V_{FC}$	$(I_{Bat} = 0)$
	Battery Mode	Emergency	
	Hybrid Mode	No direct transition possible Transition via Fuel Cell Mode or Landing Mode	
	Landing Mode	$V_{Bat/OCV} < V_{FC}$	$(I_{Bat} < 0)$
Landing Mode	Idle Mode	Torque = 0	
	Fuel Cell Mode	No direct transition possible Transition via Hybrid Mode or Charging Mode	
	Battery Mode	Emergency	
	Hybrid Mode	$V_{Bat/OCV} > V_{FC}$	$(I_{Bat} > 0)$
	Charging Mode	$V_{Bat/OCV} < V_{FC}$	$(I_{Bat} < 0)$
Idle Mode	Fuel Cell Mode	Torque = 0	
	Battery Mode	Torque = 0	
	Hybrid Mode	Torque = 0	
	Charging Mode	No direct transition possible Transition via Fuel Cell Mode	
	Landing Mode	No direct transition possible Transition via Hybrid Mode	
Battery Mode (Emergency)	Idle Mode	Torque = 0	
	Fuel Cell Mode	After fault removal	
	Hybrid Mode	After fault removal	
	Charging Mode	After fault removal	
	Landing Mode	Emergency Only modified Landing Mode (FC still disconnected) allowed	

2.2.1. Switching between Fuel Cell Mode and Hybrid Mode

The aircraft takes off in Hybrid Mode and then switches to Fuel Cell Mode. The switching procedure that needs to be followed when changing between Hybrid Mode and Fuel Cell Mode depends on the requested power of the system. A smooth transition between those two modes without voltage and current spikes is only possible by switching above the hybrid point (blue line left of the hybrid point in Figure 5a, marked in yellow). If the power demand is high, so that the system voltage is below the hybrid point in Hybrid Mode, the power must first be reduced until the hybrid point is reached before switching to Fuel Cell Mode. For this mode change, the battery current must be zero ($I_{Bat} = 0$) and consequently, the battery voltage must be lower than the fuel cell voltage ($V_{Bat} < V_{FC}$). When switching back into Hybrid Mode, the same principle applies and the power must be reduced until the hybrid point is reached and the battery voltage is lower than the fuel cell voltage ($V_{Bat} < V_{FC}$), before switching to Hybrid Mode [33].

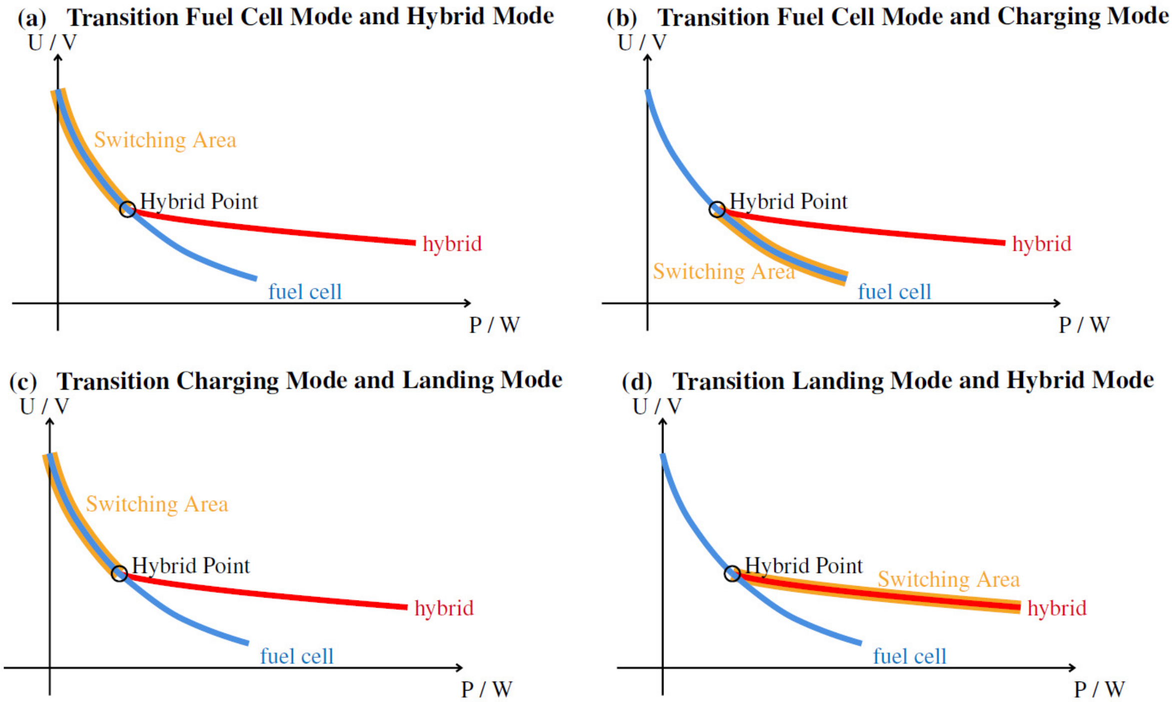

Figure 5. Allowed switching areas for different mode transitions: (**a**) Switching between Fuel Cell Mode and Hybrid Mode. (**b**) Switching between Fuel Cell Mode and Charging Mode. (**c**) Switching between Charging Mode and Landing Mode. (**d**) Switching between Landing Mode and Hybrid Mode.

2.2.2. Switching between Fuel Cell Mode and Charging Mode

The procedure that needs to be followed for a smooth transition between Fuel Cell Mode and Charging Mode depends on the requested power of the system as well. In this case, switching without voltage and current spikes is only possible when the fuel cell voltage is below the hybrid point and smaller than the OCV of the battery ($V_{FC} < V_{Bat}$) as shown in Figure 5b. If the system does not yet meet these switching conditions, the power must first be increased until the hybrid point is reached. If the system is operating in cruise phase and already operates at lower voltages than the hybrid point, then the switching conditions are already fulfilled and the system can switch directly into Charging Mode. Once the PMS has switched to Charging Mode, the power can be reduced until the system voltage is above the hybrid point ($V_{FC} > V_{Bat}$) and the difference in voltage will then charge the battery. The system voltage in this situation remains at the level of the hybrid point and the power is split between the inverter, which provides the required power for propulsion during descent to the motor and the battery which will be charged with the remaining power. The current available for charging the battery therefore depends on the required power of the inverter. A lower required inverter power results in a higher charging current. To switch back into Fuel Cell Mode, the power must be again increased until the system voltage is below the hybrid point, the charging current is zero ($I_{Bat} = 0$) and the fuel cell voltage is lower than the voltage of the battery ($V_{FC} < V_{Bat}$) [33].

2.2.3. Switching into Landing Mode

To switch from Charging Mode to Landing Mode, the current from the battery must be negative ($I_{Bat} < 0$) and should charge the battery. Due to diode D2 from Figure 4 no current will flow from the fuel cell through switch S2 while the voltage of the fuel cell is higher than the OCV of the battery ($V_{Bat/OCV} < V_{FC}$). In this voltage range that is marked in Figure 5c, the mode can be switched from Charging Mode to Landing Mode without current and voltage peaks occurring. According to the flight power profile shown in Figure 1, the power required during descent by the system for propulsion is so low that the battery can be charged via the fuel cell. In this situation, the voltage is already in the range ($V_{Bat/OCV} < V_{FC}$) that enables switching to Landing Mode. The Landing Mode offers safety against overvoltage due to the closed battery path should the electric motors act as generators. Additionally, this mode offers the instant availability of the maximum power from the battery and fuel cell without having to switch modes again should the aircraft have to take-off again.

In the event of a go-around, the pilot can switch from Landing Mode to Hybrid Mode after the restart. This is possible as soon as the OCV of the battery is higher than the voltage of the fuel cell ($V_{Bat/OCV} > V_{FC}$) and the battery current is positive ($I_{Bat} > 0$) as shown in Figure 5d. The opposite transition is possible under the same conditions.

A transition from Fuel Cell Mode into Landing Mode is also possible, should it be required. This might for example be the case if battery charging is not required since the battery is already charged or because the power demand is such that the pilot has not switched into Charging Mode yet. In this case, a direct transition is not possible, but can be performed via switching into Hybrid or Charging Mode first before entering Landing Mode. The opposite transition from Landing Mode back to Fuel Cell Mode is achieved in the same way.

As already mentioned, Battery Mode is an emergency mode in case of a fuel cell failure. Nevertheless, a transition from Battery Mode into Landing Mode is necessary for safely landing the aircraft. Since the voltage is determined solely by the battery in Battery Mode, the switch S3 from Figure 4 can be closed without further steps. S1 and S4 from Figure 4 however have to remain open, resulting in a modified Landing Mode.

3. Results and Discussion

3.1. Experimental Verification

To verify the defined switching procedures, the mode transitions were performed in a previously described laboratory setup [25]. The setup emulates the behavior of the fuel cell and the battery using two electronic sources. The two DC sources are controlled to emulate the behavior of the battery and fuel cell to be able to examine possible hybrid configurations as flexibly as possible. The emulation of the fuel cell is based on data from one fuel cell stack (HD10; Power: 10 kW; Cummins Inc., Columbus, IN, USA; prior Hydrogenics) and the battery emulation on a battery system representing 20 serial cells of a high-energy battery module (SLPB120255255; Kokam Co., Ltd., Suwon, Republic of Korea) battery. The two sources are linked to the inverters through the PMS. The status of the switches in the PMS for the respective modes is shown in Figure 4. The power output and therefore the voltage level in the system can be changed by increasing or decreasing the torque in the motor. In this manner, the switching conditions defined in Table 1 can be met and the operating mode of the PMS can be changed.

Exemplarily, the transitions from Hybrid Mode to Fuel Cell Mode, from Fuel Cell Mode to Charging Mode and back can be seen in Figure 6. Figure 6a,b show the voltage and current of the fuel cell, the battery and the inverter when changing from Hybrid Mode to Fuel Cell Mode. This corresponds to the transition from the take-off phase to the cruise phase. In Hybrid Mode, both the fuel cell and the battery contribute current. The sum of the fuel cell (blue) and the battery (yellow) current results in the inverter (red) current. The deviations seen between the inverter, fuel cell and battery voltage can be traced to losses in the experimental setup (wires, switches, diodes) [25]. In order to switch from Hybrid Mode to Fuel Cell Mode, the power is reduced to fulfill the above described switching criteria. Power is reduced until the voltage level of the fuel cell is greater than the voltage level of the battery in second 35. The fuel cell voltage is now above the hybrid point voltage and the battery current is zero. The switching condition ($V_{Bat} < V_{FC}$) is fulfilled and the switching process to Fuel Cell Mode can now be executed without voltage differences and current peaks. The shaded areas in Figure 6, shows the validity of the switching condition. In the lab test, the power is lowered somewhat further to increase the voltage difference between the fuel cell and the now inactive battery before switching. At second 60 (marked by the black line), after 10 s of stable voltage level, the system is switched from Hybrid Mode to Fuel Cell Mode. After changing the mode and giving additionally 10 s to stabilize, the power is increased again. The battery is now disconnected from the system and has no influence on the system performance. Its current remains constant at zero and its voltage remains at its OCV. The system is now powered by the fuel cell only and the voltage level of inverter and fuel cell almost equal.

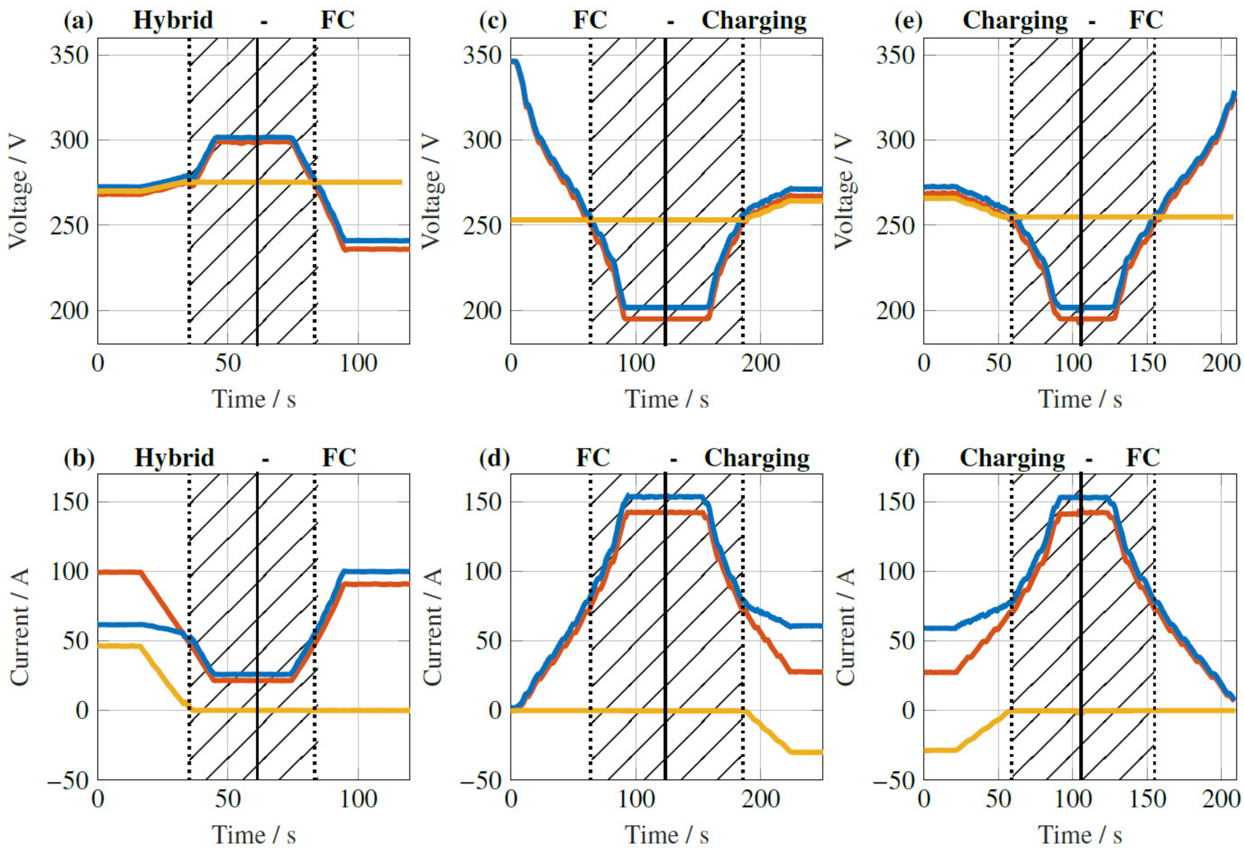

Figure 6. Current and voltage of a battery, fuel cell and inverter during switching procedures from (**a**,**b**) Hybrid Mode to Fuel Cell Mode; (**c**,**d**) Fuel Cell Mode to Charging Mode; (**e**,**f**) Charging Mode to Fuel Cell Mode.

Figure 6c,d show the measured voltage and current of the fuel cell, the battery and the inverter when changing from Fuel Cell Mode to Charging Mode. This represents the transition from the cruise phase to the descent phase. In the first section of Figure 6c,d, the power increases. Since the battery is not connected in Fuel Cell Mode, the entire power is provided by the fuel cell (I_{Bat} = 0) and as power increases the voltage level provided by the fuel cell decreases. From second 64 onwards, the fuel cell voltage is lower than the OCV of the battery. From here on, the necessary switching condition ($V_{Bat} > V_{FC}$) for switching from Fuel Cell Mode to Charging Mode is fulfilled. In the lab test, the power is increased further and in second 114 (black line) the modes are switched. As before the gray area shows where the switching conditions are met. Once the system is switched to Charging Mode, the power is reduced again and the voltage of the fuel cell rises above the voltage of the battery. From second 186, the fuel cell voltage is greater than the battery voltage ($V_{Bat} < V_{FC}$) and the battery is now being charged due to the voltage difference ($I_{Bat} < 0$), which can be seen from the negative battery current in Figure 6d.

The lower the power requirement of the motor, the more energy from the fuel cell can be used to charge the battery. To return to Fuel Cell Mode, the motor power must be increased again until the fuel cell voltage is lower than the voltage of the battery ($V_{Bat} > V_{FC}$). This is shown in Figure 6e,f. In the shaded area, the previously described switching criteria for switching back to Fuel Cell Mode is fulfilled and the switching operation can be initiated.

3.2. Power Reduction during Switching

As demonstrated in the previous section, changing from one mode to the other without current and voltage spikes is possible by adapting the power output to fulfill the switching conditions. This means that during the switching procedure the power output is determined by the switching process and not by the power demand of the flight phase. There will for example be a power reduction when changing from Hybrid Mode during take-off to Fuel Cell Mode for cruise and an increase in power when changing into Charging Mode.

A short power reduction does not impede the application of the proposed direct hybrid in aviation as modern commercial aircraft have glide ratios between 15 and 20 [37,38], and a short reduction or increase in power does not endanger the aircraft. An increase or decrease in power however affects the longitudinal stability of the aircraft [39], which needs to be countered by the aircraft dynamic control. Still, the power reduction due to a change in mode should be as small as possible during a flight.

The necessary power reduction when changing from Hybrid Mode into Fuel Cell Mode for an exemplary hybrid system based on the voltage–power curves of a 10 kW PEM fuel cell stack (HD10; Power: 10 kW; Cummins Inc. USA; prior Hydrogenics) and a high-energy battery module (SLPB120255255; Kokam Co., Ltd., Republic of Korea) was examined with the help of a Matlab simulation. For the simulation, data from a previous study [25] were linearized and an example system consisting of one motor, one fuel cell stack and one battery module was considered. Figure 7a shows the resulting voltage–power curve of the fuel cell–battery hybrid system. Point 1 is the starting point and here a power of 4 kW is provided while the system is in Hybrid Mode. 60% of the power are provided by the battery system and 40% from the fuel cell system. This setpoint was chosen, so the fuel cell system can provide the same power of 4 kW by itself at a voltage level that is above the minimum voltage level of 65 V determined by the inverter. The battery was chosen so that the hybrid system could provide the full power even at a battery SOC of 20%. For the examined situation, an SOC of 80% was assumed.

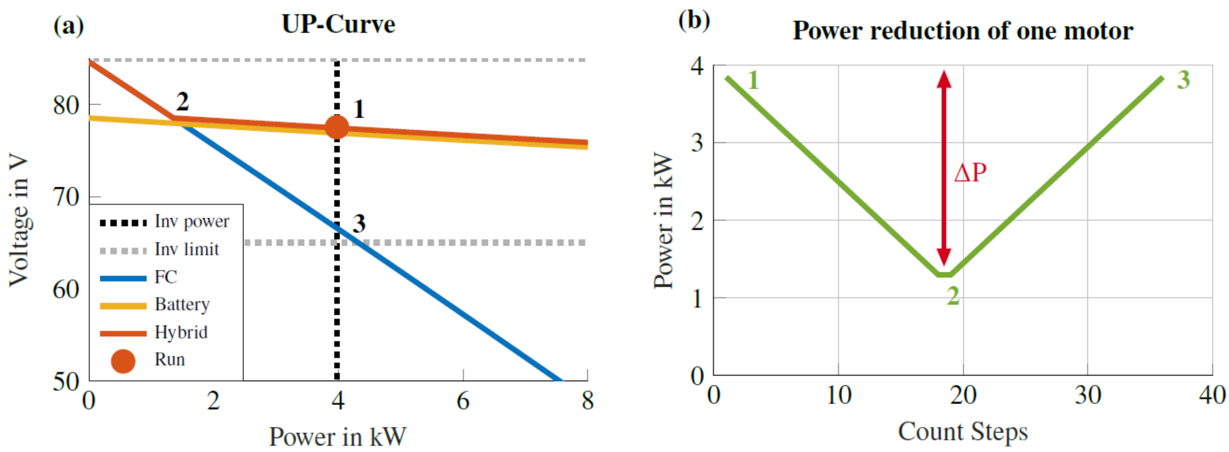

Figure 7. (**a**) Linearized voltage–power curve of the hybrid system [21]. (**b**) Power reduction for switching in a 4 kW scenario from Hybrid Mode to Fuel Cell Mode with one powertrain.

Setting the total power to 4 kW enables the system to also be operated in Fuel Cell Mode at the same power. This operating point is marked as point 3 in Figure 7a. To switch from Hybrid Mode to Fuel Cell Mode, the power must first be reduced to meet the switching conditions $V_{Bat} < V_{FC}$ from Table 1. In Figure 7b, the line between number 1 and number 2 represents this power reduction ΔP. After switching to Fuel Cell Mode in point 2, the power can be increased back to the original power level of 4 kW along the line between points 2 and 3 in Figure 7b. It can be seen that the examined single-motor system must reduce the power by ΔP = 2.6 kW or 65% to switch from Hybrid Mode to Fuel Cell Mode, as shown in Figure 7b.

An aircraft propulsion system that comprises two separate powertrain units as shown in Figure 8, with a fuel cell, a battery, and a motor each, is a possible mitigation strategy. The logical switching sequence of a two separate powertrain propulsion system for a change from Hybrid Mode to Fuel Cell Mode is as follows: Both powertrains start in Hybrid Mode. The strategy for changing from Hybrid Mode to Fuel Cell Mode with two motors starts by reducing the power of only one motor while increasing the power of the second motor. The total power of both motors together does not change. After motor 1 reaches the switching condition $V_{Bat} < V_{FC}$, the power management system of motor 1 can switch to Fuel Cell Mode. After motor 1 is in Fuel Cell Mode, the power of motor 2 will be reduced, and motor 1 will balance the power reduction and increase its power. After motor 2 reaches the switching conditions, the power management system of motor 2 can switch to Fuel Cell Mode as well. Now both independent systems are in Fuel Cell Mode and the power can again be shared equally between the motors. Due to the unequal power distribution during the switching procedure the two propellers will generate different thrust and cause a yawing moment [39]. In order to not change course, the aircraft has to compensate for this by counter-steering.

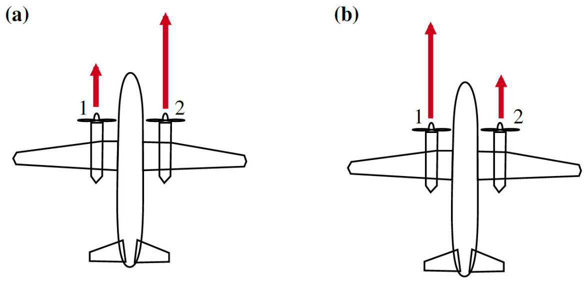

Figure 8. Power strategy for switching procedures with two motors: (**a**) Reducing the power of motor 1 and increase the power of motor 2. (**b**) Reducing the power of motor 2 and increase the power of motor 1.

The impact of the difference in thrust per wing is decreased if the number of propellers and power train units per wing is increased to two or more [40]. Such a distributed propulsion system is advantageous from a control and stability point of view [41] and enables, for example, two motors on the left wing and two motors on the right wing to compensate for each other when switching from Hybrid Mode to Fuel Cell Mode. In any case of combining powertrain units as multiples of two, the power change issue during switching can be overcome by implementing an appropriate control strategy that runs the above-mentioned sequence, enabling the switching from one mode to another.

Figure 9a shows the simulation results for switching from Hybrid Mode to Fuel Cell Mode if two powertrain units are installed and the described strategy of sequential switching is followed. In the example, both systems start in Hybrid Mode and provide a propulsion power of 2 kW each. The sum of propulsive power of both systems equals the total power of 4 kW of the previous example. The power curves of the fuel cell and the battery are scaled as well, so that the hybrid ratio is 60% battery and 40% fuel cell as in the previous example. In both systems, the fuel cell can supply the full 2 kW due to the scaling and still remain within the inverter voltage limits. To change both powertrain units to Fuel Cell Mode, they are switched at different moments. It can be seen in Figure 9a, that the power of motor 1 is first reduced from 2 kW in point 1 to 0.65 kW in point 2 to meet the switching conditions and switch to Fuel Cell Mode. At the same time, the power of motor

2 is increased to compensate for the reduction in power from motor 1. After motor 1 has successfully been switched to Fuel Cell Mode, the power of motor 1 is increased and the power of motor 2 is reduced again until motor 1 and 2 have the same power of 2 kW each, as before switching. In the next step, the power of motor 2 is reduced to reach the switching conditions for motor 2 in point 5. Motor 1 should now compensate for the power reduction in motor 2, but motor 1 is already in Fuel Cell Mode and at the limit of the inverter voltage. Therefore, the power of motor 1 cannot be increased beyond 2.3 kW, which is why the total power decreases as shown in Figure 9a. After the switching conditions of motor 2 are reached at point 5, it is also changed to Fuel Cell Mode and its power can be increased again. In the case shown in Figure 9a, the total power reduction is now only 1.1 kW or 25%, which is a significant improvement compared to the single-motor system discussed above.

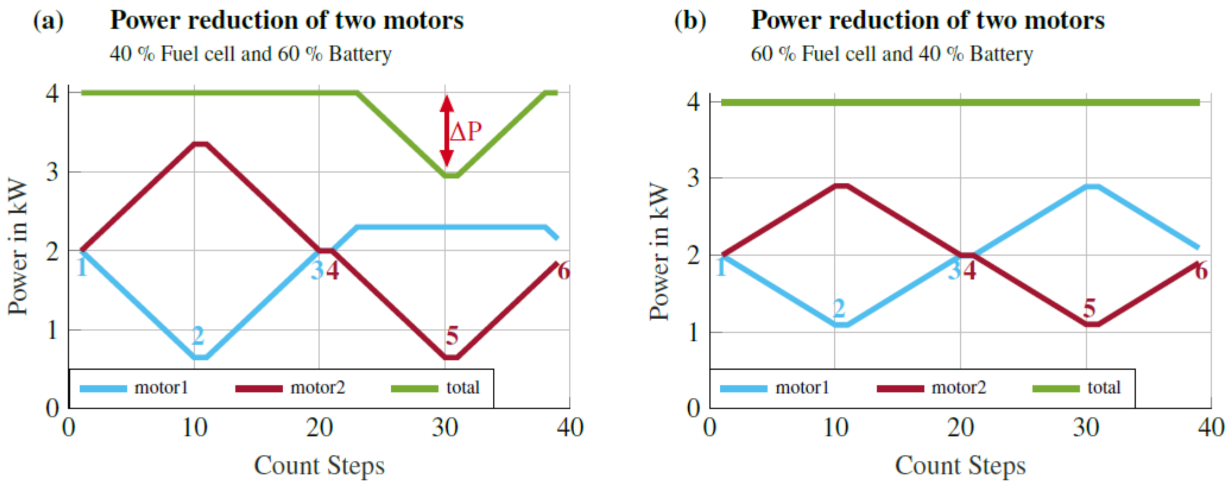

Figure 9. Power reduction for switching from Hybrid Mode to Fuel Cell Mode for a propulsion system with two independent power trains with two different hybrid ratios: (**a**) 40% fuel cell and 60% battery at 2 kW motor power; (**b**) 60% fuel cell and 40% battery at 2 kW motor power.

The distribution and required reduction in power during the switching procedure also changes when the hybrid ratio of the powertrains is changed by, e.g., increasing the size of the fuel cell. By inverting the ratio between the fuel cell and the battery, that is by examining a ratio of 60% fuel cell and 40% battery power at 2 kW for both motors, the switching process can be easily be executed without power reduction in the overall system as shown in Figure 9b.

The results show how the dimensioning of the fuel cell and the battery as well as the operating points have a strong impact on the required switching procedures of a direct hybrid system.

4. Conclusions

In the examined fuel cell-based direct hybrid electric powertrain, a fuel cell and a battery are connected in parallel without an intermediate DC/DC converter. A power management system consisting of switches and diodes enables operation in different operation modes, for example, Fuel Cell Mode, Hybrid Mode, Charging Mode or Landing Mode. The modes are selected to match the power demand during different flight phases like take-off, climb, cruise, descent and landing.

For a safe operation, certain conditions must be met before changing from one mode to the other in order to make sure that no operational limits of any component of the powertrain is exceeded and to protect components from current or voltage spikes. The necessary conditions for zero current operation of the switches to avoid the formation of arc in the relays were defined, and switching procedures for the transition between different modes (fuel cell, battery, hybrid, charging and landing) were developed and experimentally verified, using an emulated two-source system that mimics the behavior of the hybridized fuel cell and the battery.

The switching conditions and procedures were confirmed for an exemplary system that provided a combined power output in Hybrid Mode of 4 kW with 40% contribution from the fuel cell and 60% from the battery. The system was also able to provide the same power output in Fuel Cell Mode and the mode changes succeeded without voltage and current peaks. It was found that for the change from Hybrid Mode to Fuel Cell Mode in the examined system, the power needs first to be reduced by 65% before switching in order to meet the switching requirements. The necessary power reduction can be significantly lowered by adding a second powertrain, which diminished the overall power reduction during the transition from Hybrid Mode to Fuel Cell Mode to 25%. It was also shown that by modifying the hybrid ratio of a fuel cell and a battery, the power reduction during mode change in the two-powertrain system can even be completely compensated, when using a higher fuel cell share.

Future work will focus on the duration of the switching times during which the power is determined by the switching procedure instead of the power demand of the power train. It is to be expected that the time required for switching can be limited to a few seconds as electric motors [41] as well as batteries have a very fast response time. A change in fuel cell power can also be achieved almost instantaneously [42], despite the fact that equilibrium conditions at the fuel cell for the new operating point might only be reached after several minutes as the dynamic behavior of fuel cells is complex [43] and gas supply, cell temperature and humidity all play a role. A short power reduction as described in the case for the single-motor system or an uneven distribution of thrust on both sides of the aircraft as in the two-propulsion-unit scenario does not impede the application of the proposed direct hybrid in aviation as modern commercial aircraft have good glide characteristics and a short reduction or increase in power or a short uneven distribution of thrust does not endanger the aircraft.

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Abbreviations

The following abbreviations are used in this manuscript:

DC	Direct current
Inv	Inverter
I_{Bat}	Current of a battery in A
OCV	Open circuit voltage
PMS	Power management system
P	Power in W
PEM	Polymer electrolyte membrane
$P_{request}$	Power demand of the propulsion system in W
SOC	State of charge
U_{inv_max}	Max. voltage of the inverter in V
U_{inv_min}	Min. voltage of the inverter in V
V_{FC}	Voltage of a fuel cell in V
V_{Bat}	Voltage of a battery in V

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