Variable Displacement Hydraulic Motors used for High Lift Systems of Commercial Aircrafts (on the example of the Airbus A380 Flap System)

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ABSTRACT

Power optimisation of aircraft systems lead to weight savings of structure or system parts and therefore to reduced operating costs.
High Lift Systems are used to increase the lift during take off and landing. Typical High Lift Systems of commercial aircraft comprise a Power Control Unit (PCU) which actuates the high lift surfaces. These surfaces are either located on the leading- or on the trailing edge of the wing. They are connected to actuators ("drive stations"), which are connected via the transmission system to the PCU (refer to figure 1).
This paper deals with the power and weight saving potentials by using Variable Displacement Hydraulic Motors (VDHM)on the example of the flap system of the Airbus A380.
An overview of the used design and controller architecture is also provided.

NOMENCLATURE

Δp_{man}	Manifold pressure losses	MPa
Δp_{mcv}	Control Valve pressure losses	MPa
v_{max}	Maximum Displacement	cm^3
η_{stat}	Motor Break Out Capability (efficiency)	-
η_{dyn}	Motor Dynamic Capability (efficiency)	-
T	Operating Torque at Motor Shaft	Nm
T_{hyd}	Theoretical (hydraulic) Torque	Nm
T_{aero}	Aerodynamic part of Motor Torque	Nm
i_{diffg}	Differential Gear Ratio from motor shaft to PCU shaft	-

1. INTRODUCTION AND OVERVIEW

The PCUs, used to actuate the high lift surfaces are typically composed of a differential gear box, on which two hydraulic motors (inline axial piston type), brakes, manifolds, solenoid valves and sensors are mounted. The two hydraulic motors are connected via the manifolds to two different hydraulic systems. Both motors are commanded simultaneously (all Airbus aircrafts) during the operation of the high lift surfaces. The speed summing differential gear guides the mechanical power of both motors to a single output shaft, which distributes the power via the transmission system to both wings drive stations

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On all Airbus aircrafts, starting from the A300 through A340, *fixed* displacement axial piston type motors have been used. The use of *variable* displacement motors on the Airbus A380 is the first application on a commercial aircraft (refer to figure 2). The reason for this is, that based on the layout consideration of the motors and the operation conditions, the VDHM technique offers a big flow saving potential, which was transferred into considerable weight savings.

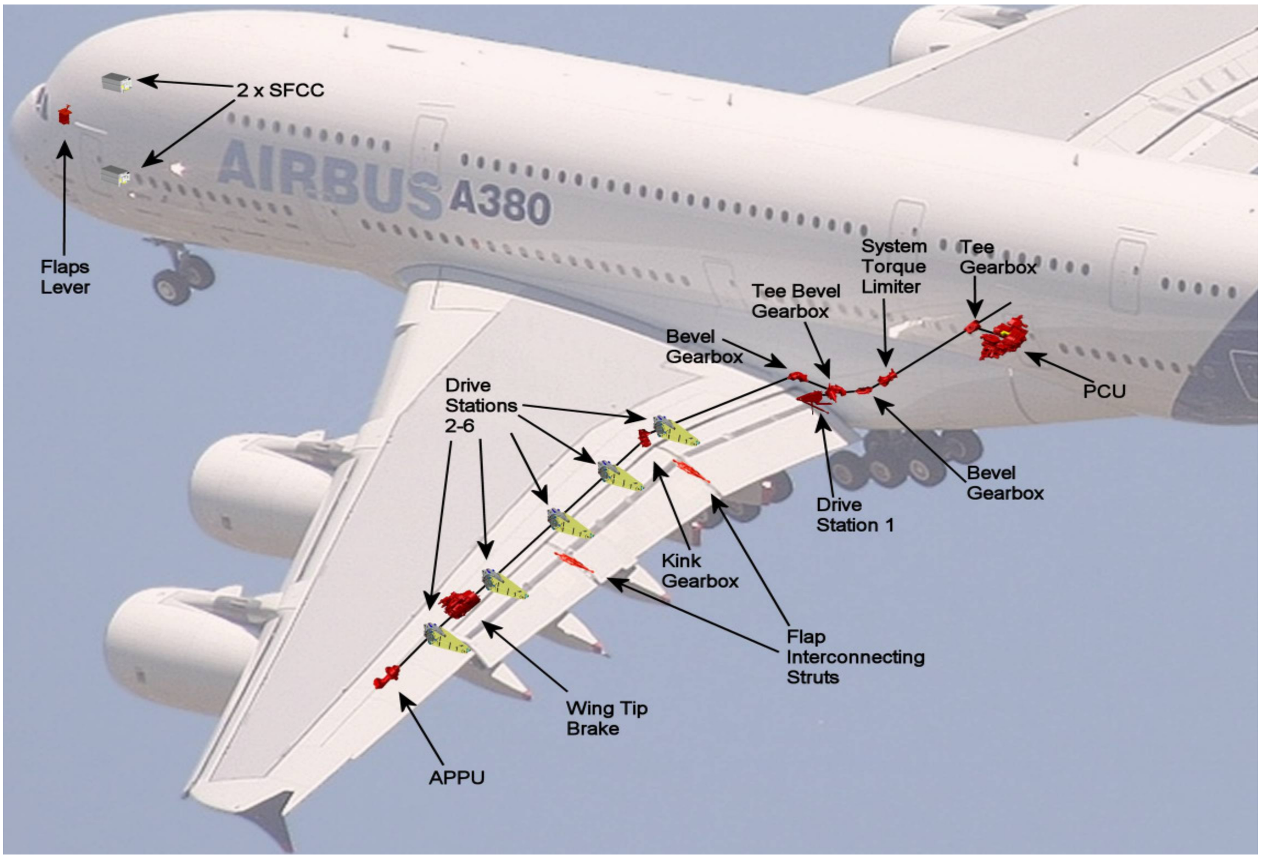

Figure 1, Flap High Lift System of Airbus A380

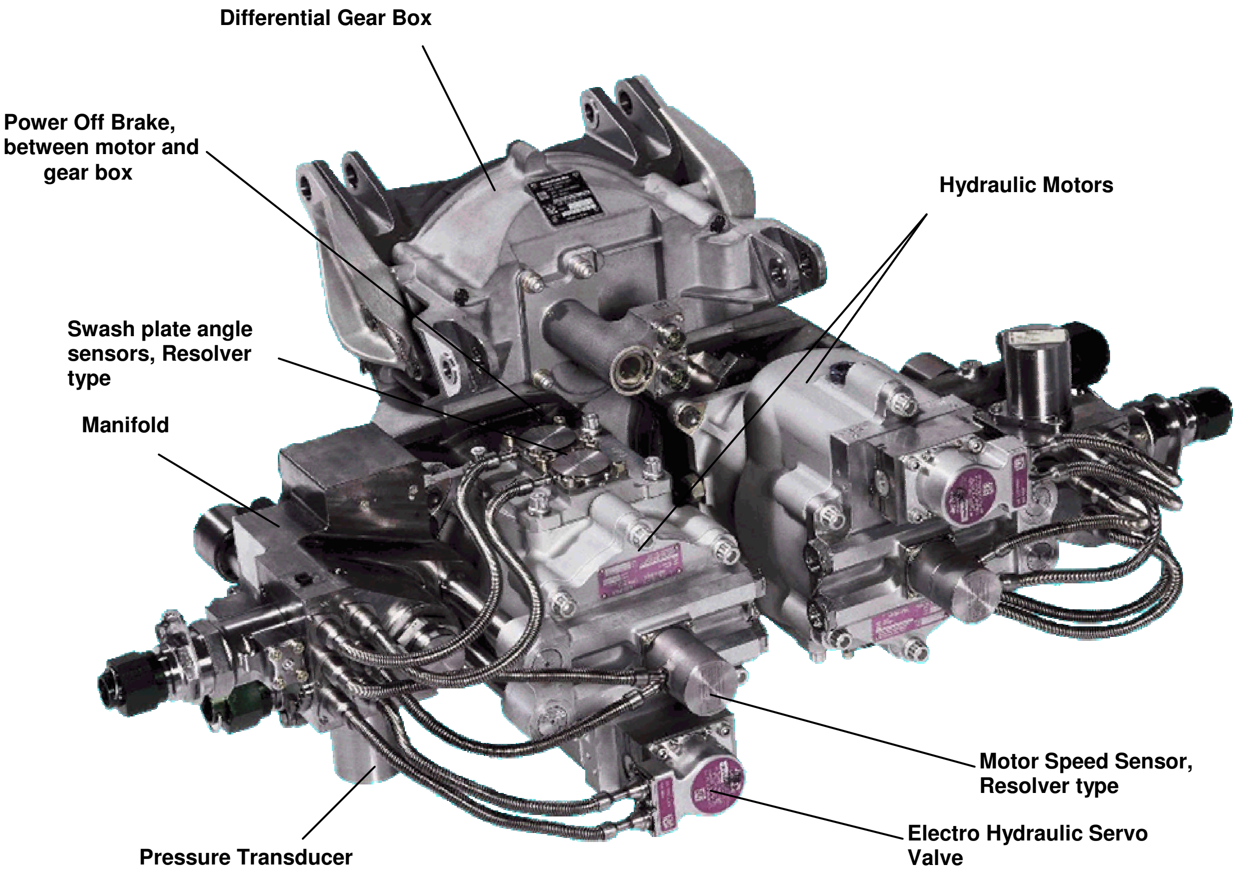

Figure 2, Power Control Unit of A380 Flap System

2. COMPARISON BETWEEN FDHM AND VDHM TECHNOLOGY

In the following chapters basic control functions and principle pressure losses of the two concepts are compared.

2.1 FDHM concept:

Fig. 3 shows a simplified FDHM hydraulic circuit. A main control valve is used to command sense of rotation and to ensure constant speed behaviour over a wide load range. Hence, motor torque is controlled indirectly by the main control valve, controlling the pressure drop over the motor. Further functions, as there are: “Manifold pressure on/off” or “low/high speed” are enabled or disabled by solenoid valves.

This concept leads to a highly complex manifold design with significant pressure losses over the manifold bores (Δp_{man}) or over the main control valve (Δp_{mcv}).

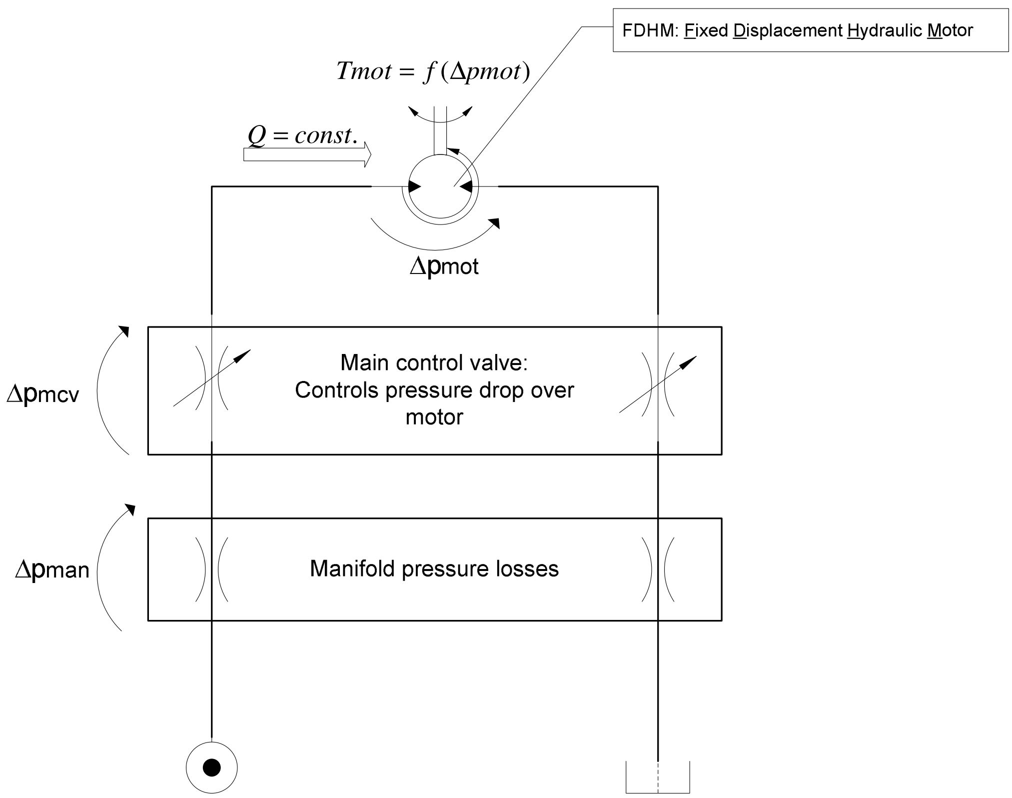

Figure 3, Simplified Hydraulic Circuit of FDHM Technology

2.2 VDHM concept:

Fig. 4 shows the simplified VDHM hydraulic circuit. There is no need for a main control valve. A variable displacement (over centre type) motor can change sense of rotation by adjusting the swash plate "over centre". The swash plate itself is actuated by an Electro Hydraulic Servo Valve (EHSV). Rotational sensors are used to transmit the swash plate position, which is equivalent to the motor torque, and the position of the motor drive shaft to a digital computer. Control and monitor circuits calculate the input current for the EHSV.

Deletion of a main control valve leads to a very simple manifold design. The advantage obviously is that the pressure losses are considerably lower than those of the FDHM concept. Under comparable loading conditions, the displacement of the motor can be adjusted therefore to a lower value than it would be needed for the FDHM, because nearly the full supply pressure acts on the motor. The VDHM consumes only the hydraulic power that is needed to drive the system with the results that the aircrafts hydraulic system is relieved and heat emission into the hydraulic fluid is kept as a minimum.

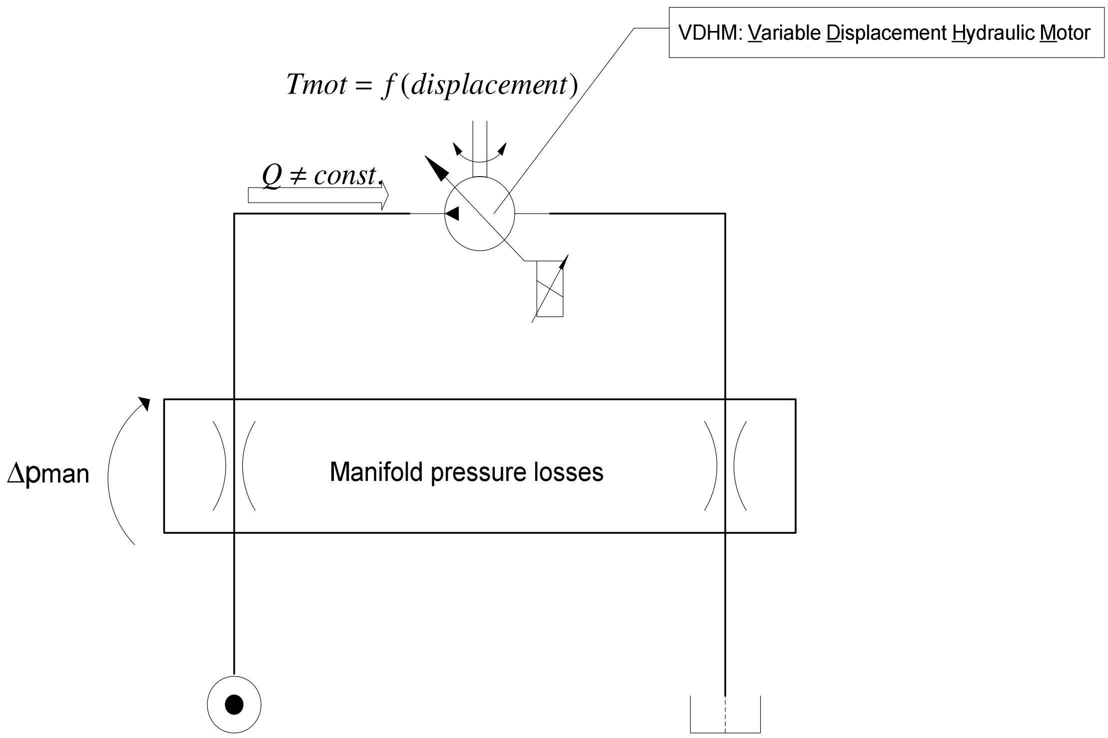

Figure 4, Simplified Hydraulic Circuit of VDHM Technique

Comparison of concept efficiency:

Figure 5 compares the power losses and the mechanical output power between a FDHM and a VDHM PCU of the A380 flap unit size. The size of the green portion (output power) can be used as efficiency indicator for the unit (hydraulic and mechanic efficiency).

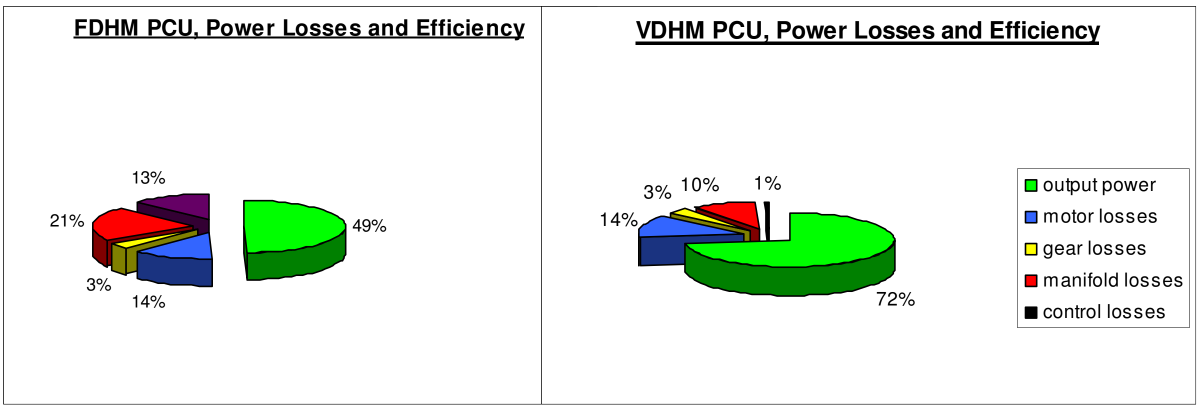

Figure 5, Comparison of Efficiency between FDHM and VDHM Concept

3. MOTOR LAYOUT REQUIREMENTS AND POWER / WEIGHT SAVINGS

3.1 Determination of Maximum Displacement

The maximum displacement, v_{max} is defined by the landing phase of the aircraft, at the point when the system starts to extend the flap surface (system "break out" phase).
The following conditions are required for the motor layout:

- Break Out shall be possible under maximum loading conditions (high aerodynamic loads and high transmission system drag torques at low temperatures)

- Break Out shall be possible under low pressure conditions (75 - 80 % of nominal pressures). The nominal hydraulic system pressure of the A380 is 345 bars. The requirement to use low pressure conditions, results for the layout of the A380 motor to use a Δp of 265 bars instead of 345 bars.

- Break out capability (η_{stat}) of the hydraulic motor has to be taken into account.

The required maximum displacement for the break out phase is therefore:

$$v_{\max} = \frac{T \cdot 2 \cdot \pi}{\Delta p \cdot \eta_{stat} \cdot i_{diffg}}$$

The motor break out capability ("static efficiency") η_{stat} is determined by the ratio of the theoretical hydraulic torque and the usable torque at the motor shaft.

$$\eta_{stat} = \frac{T}{T_{hyd}}$$

Axial piston motors for aircraft applications reach static break out capabilities of 0, 7 at the minimum.

The torque, required to be driven by the motor during the break out phase is determined by the aerodynamic loads acting on the flap surfaces and the drag torques within the transmission system for a specific environmental temperature case (-40℃). The required torque for the hydraulic motor can be expressed by the pure aerodynamic torque, multiplied by the factor tr_{loss} to take into account the drag torque losses of the components of the transmission system (gear boxes, joints, etc).

The factor can be expressed by:

$$tr_{loss} = \frac{T_{aero}}{T}$$

For high lift systems of the A380 flap size, the factor tr_{loss} varies between 0, 35 - 0, 45. This means that aerodynamic loads are only 35 - 45% contributing to the overall motor loads. Hence, the transmission system drag torques to the overall motor break out loads cannot be neglected.

From the layout considerations above, the maximum adjustable displacement of the A380 VDHM motor was determined to be $28cm^3$. The same motor size would have been chosen for the fixed displacement motor, if this concept was realised.

The following table gives on overview of the VDHM design parameters:

Motor Type	Inline axial piston (9 off)	
Supply Pressure Range	265 - 345 bar	Airbus A380 is first commercial aircraft with 5000 psi system
Maximum Motor Displacement	$28\ cm^3$	
Maximum allowed Flow	80 litre/min	Limited by power limitation controller
Nominal Motor Speed	5900 rpm	
Minimum Break Out Torque	80 Nm	
Swash Plate Angle Range	+/- 18°	Over Centre Design
Type of EHSV	4/2 Way, 2-stage, Jet Pipe	

3.2 Comparison of Power (Flow) Demands for Dynamic Operation

This chapter compares the flow demand of both concepts during dynamic operation (system in motion). The comparison is based on the motor layout considerations made in chapter 3.1.
As mentioned above, PCUs for commercial aircrafts are speed controlled units. It is required that the speed of the PCU output shaft remains constant over a wide load range. To realise this with the VDHM concept, a speed and torque control loop is implemented on a digital controller (SFCC: slat flap control computer), refer also to chapter 4.0.

During dynamic operation, once the High Lift System achieved break out, the motor loads are considerably lower compared to the break out phase due to the following aspects:

- The dynamic efficiency of inline axial piston motors reach up to η_{dyn} = 0, 9. This is considerably higher compared to the break out efficiency of 0, 7.
- Due to warming up effects within the transmission system, the contribution of the transmission system drag torques to the motor loads are lower that in the break out phase. tr_{loss} varies for dynamic operation from 0, 45 to 0, 65.

Both aspects lead for the VDHM concept to the following situation:
Maintaining the required speed, the controller is able to adjust during dynamic operations lower displacements than during the start up phase. As a maximum 65% of the full motor displacement is needed to extend the flap system once it is in motion.
In addition with the efficiency benefits as outlined in paragraph 2.1., this leads to considerable flow and therefore power savings.
Moreover, the “power limitation mode”, a special control task, calculates the actual flow to the motor in dependency of the speed and swash plate angle feedback. If due to very high loads, the maximum allowable flow of 80 litre/min tends to be exceeded, the motor speed is automatically reduced.

The following figures compare the flow from the hydraulic system for two operation cases for both concepts:

- Figure 6: Flaps extending during approach under maximum loading and low pressure conditions. For the VDHM concept, two curves - power limitation mode on and off - are shown.
- Figure 7: Flaps retracting after take off under aiding load conditions.

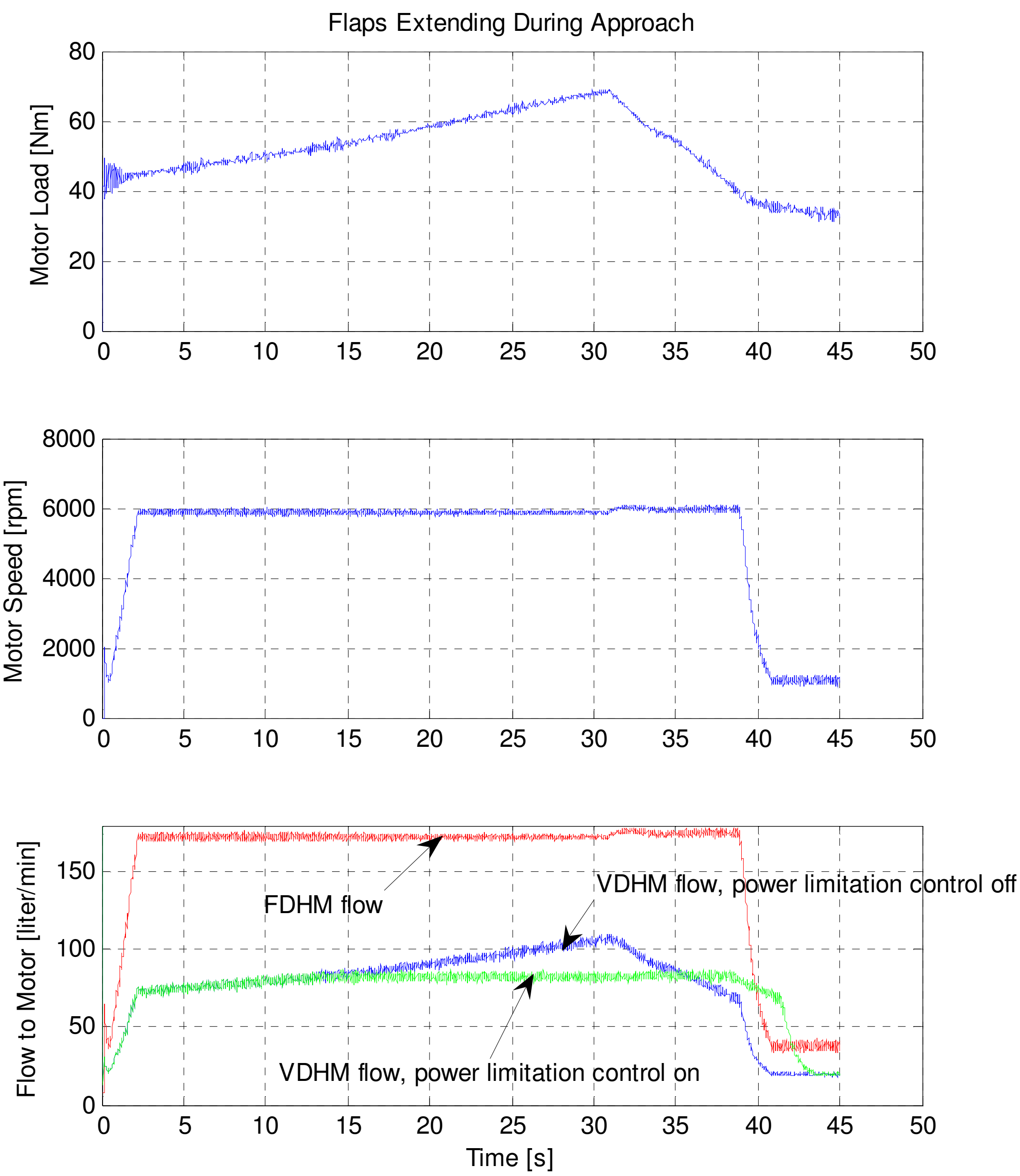

Figure 6, Comparison of Flow during Flaps Extending

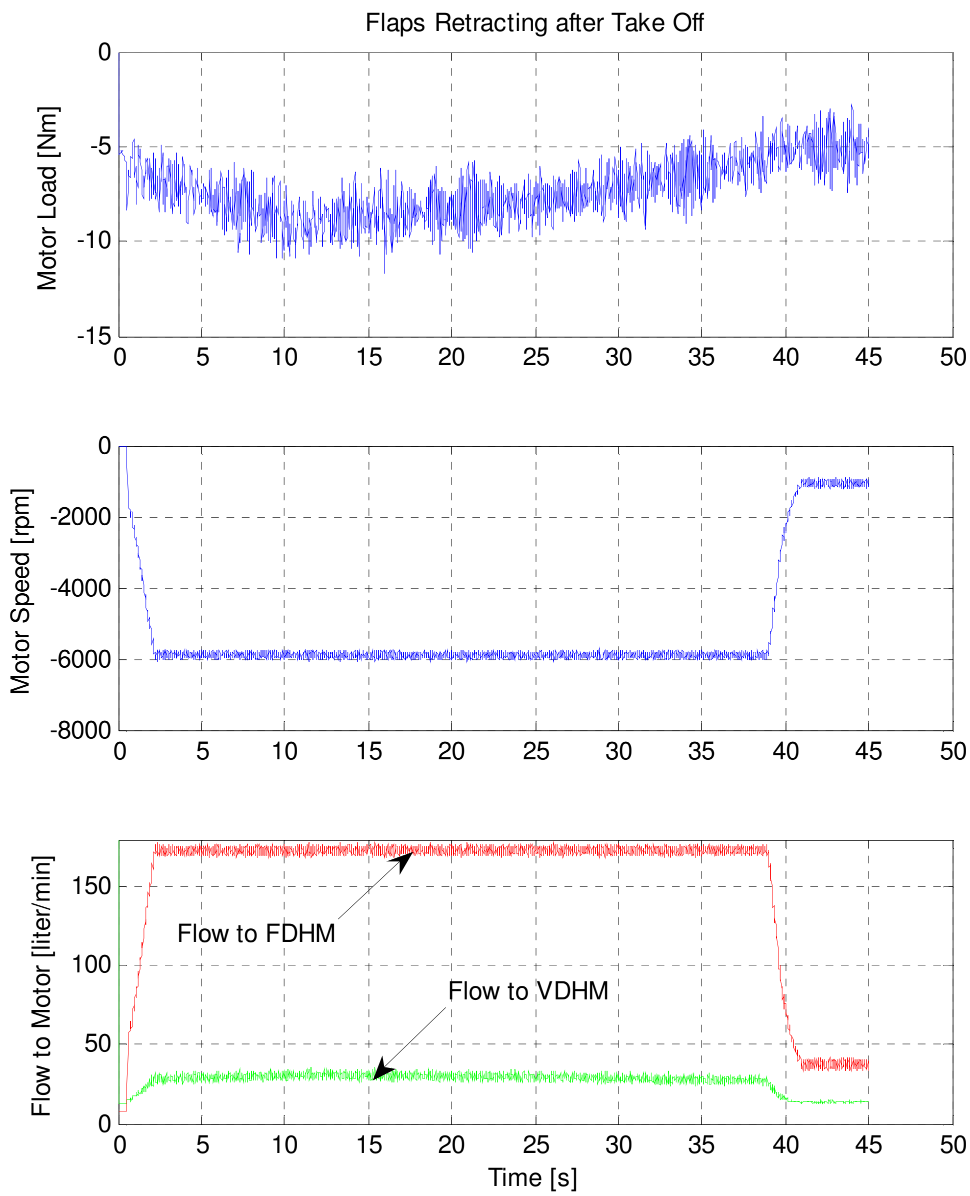

Figure 7, Comparison of Flow during Flaps Retracting

Conclusion: The figures shown above demonstrate that there is a big flow and therefore power saving advantage for the VDHM concept.

Based on these flow figures, Airbus decided during the concept phase of the A380 to chose the VDHM concept for the actuation of the High Lift Systems. As a result, parts of the aircrafts hydraulic system could be designed by using smaller tube diameters. Due to the simplification of the manifold, the PCU itself offered also a weight saving potential.

The weight savings are at least:

- Aircraft Hydraulic System: > 130 kg
- PCU: > 15 kg

4.0 CONTROLER

4.1 Control Tasks

The motor control electronic is part of the SFCC. Each of the main control tasks (speed and torque loop) run with a sample time of 2ms due to the required high dynamic bandwidth of speed and torque response:

- Torque (swash plate) response: -3dB @ 25 Hz
- Speed response (with connected transmission system): -3dB @ 2Hz

The sample time of the power limitation controller is 10ms.
Figure 8 on the next side gives an overview of the principle controller structure

4.2 Monitor Tasks

The hydraulic concept does not comprise any passive flow restricting device in order to limit the motor speed in case of failures, such as EHSV hard over. This provides a benefit to the very efficient hydraulic concept and simplifies the control loops. On the other side, there must be electronic monitors in order to prevent the motor against failure events.
A failure mode analysis showed that the following monitor tasks are needed. Most of these tasks run with a sample time of 2ms.

- Over Speed Monitor
- Speed Signal Disconnect Monitor
- Incorrect Sense Of Rotation Monitor
- Incorrect Motor Start Up Condition Monitor
- Electrical Interface Integrity Monitor

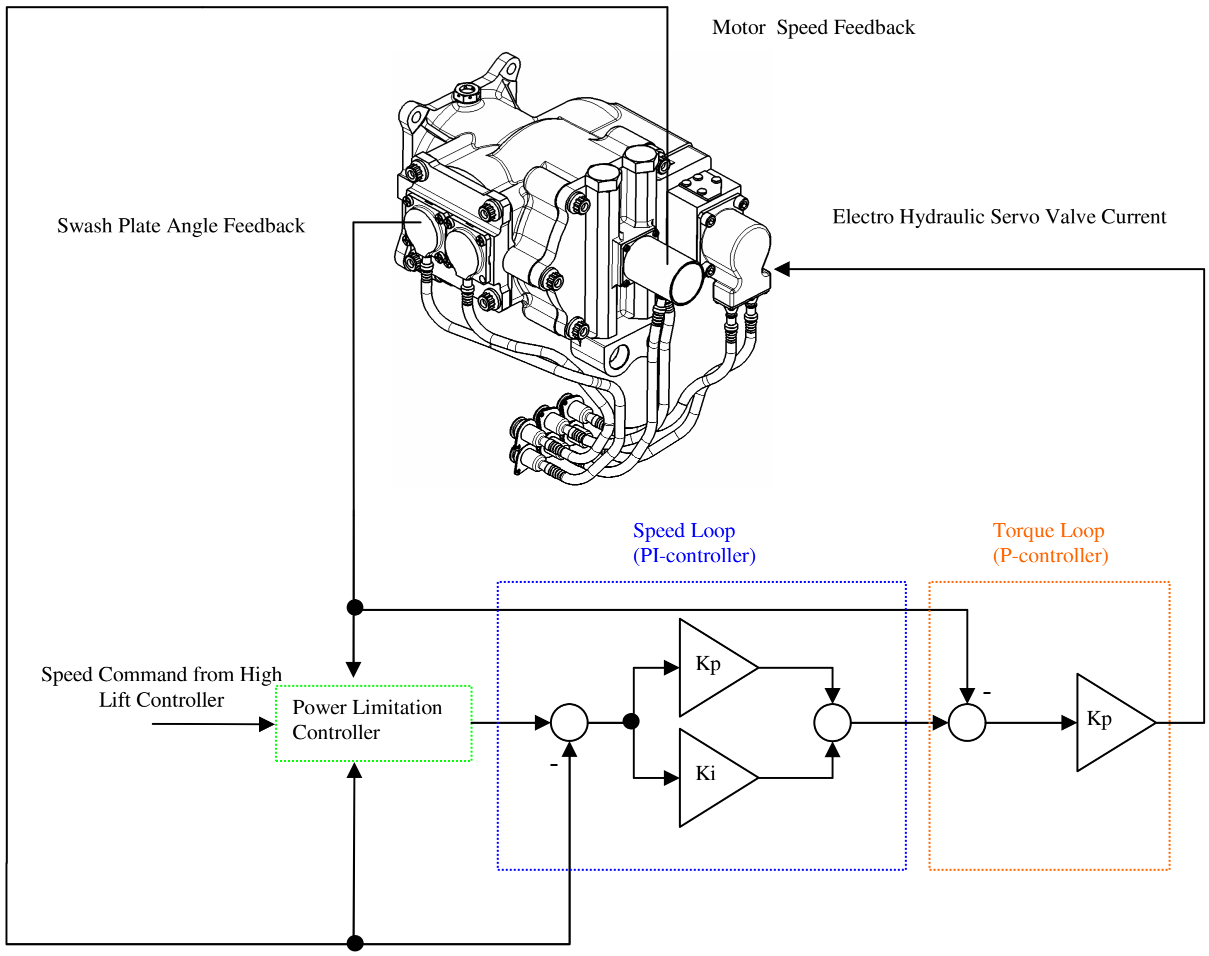

Figure 8, Controller Overview