MK100
Pressure Control Strategies
(CONFIDENTIAL)

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History:

Reasons for Changes (RC):

- Correction
- Refinement

Version	Date	Author	RC	Chapter	Change Description
1.1	30.11.2011	Scheller, Tobias	All		Initial check in from MKxxA.
1.2	17.01.2012	Treib, Alexander	All		Restructuring introduction of volumetric and overflow control illustrations
1.3	25.01.2012	Treib, Alexander	R		Creation of chapter “Gradient based volumetric pressure control using pressure sensors”
1.4	27.01.2012	Treib, Alexander	R		Update of chapter “Gradient based volumetric pressure control using pressure sensors” Update of chapter “Pump pressure control” in chapter “Overflow”
1.5	30.01.2012	Treib, Alexander	R		Creation of chapter “Pump motor control” (including the sub chapters)
1.6	07.02.2012	Neu, Andreas	R	2	Page feed added, to not disturb graphics
1.7	09.02.2012	Treib, Alexander	R		Creation of the chapter “Activation/deactivation conditions for pump pressure control for volumetric…” Rework of chapter “LPV valve control” Rework of chapter “Standard volumetric pressure control”
1.8	18.11.2013	Neu, Andreas	R	2	TSC LPF added
1.9	29.11.2013	Treib, Alexander	C		Add chapter “Technical Safety of the Hydraulic Modulator”
1.10	02.12.2013	Andreas Neu	C		Move TSC LPF to Chapter Safety of … and refine
1.11	03.12.2013	Andreas Neu	R	2, 4	Three links added
1.12	10.01.2014	Treib, Alexander	R	4.1.4, 4.1.8	Simplify description of the valve control chains Add main driver role description
1.13	21.01.2014	Treib, Alexander	R		Add link to pump failsafe Add link to valve control failsafe
1.14	28.02.2014	Treib, Alexander	R	4.1.5, 4.1.5	Redesign; add use case structure; refine supervisions
1.15	27.05.2014	Treib, Alexander	R	4.2	Create chapter “Appendix Valve current supervision”
1.16	4.06.2014	Treib, Alexander	C	4.2	Declare Umin as ADC value

1.17	7.10.2014	Treib, Alexander	R	4.1.3, 4.1.4, 4.1.4.4, 4.1.5	Mention SPI communication in chapter “Safety aspects – How to … Hydraulic Modulator…” Add new schematic in chapter “Safety aspects – How to … MCI..LPF..IV…” Add link to detailed information of initial check (chapter “Use case “power on…” Add new schematic in chapter “Safety aspects – How to …OV…”

1 Introduction

The pressure control software is separated in four functional divisions: each pressure increase and decrease for main and wheel circuits. The purpose of this document is to show these functional parts and their interaction to fulfill the task of pressure controlling.

1.1 Nomenclature

In this document constants being used in the parameter adjustment system are marked by ***Times New Roman***. Global and local variables are written in **Univers Condensed.**

2 Circuit Individual Pressure Control

2.1 Overview

The circuit pressure controller is active only if the arbitrated hydraulic circuit pressure is higher than the TMC pressure.

The evaluation of the circuit pressure control values starts after the wheel pressure arbitration. At this time 4 wheel pressure values have been calculated. The hydraulic circuit arbitration needs the arbitrated wheel pressure request values and the driver pressure request values (including total torque requests of HBA, OHB, …) of both circuit wheels to calculate the pressure which has to be adjusted by the circuit pressure controller.

Pcircuit = MAX(***Parb_wheel1, P_arb_wheel2, P_drv_wheel1, P_drv_wheel2***)

The pressure increase of one hydraulic circuit is performed by LPF valve (Low Pressure Feed) and pump (green line). MCI (Master Cylinder Isolation) valve is fully closed during pressure increase. A pressure decrease is performed by MCI valve (red line):

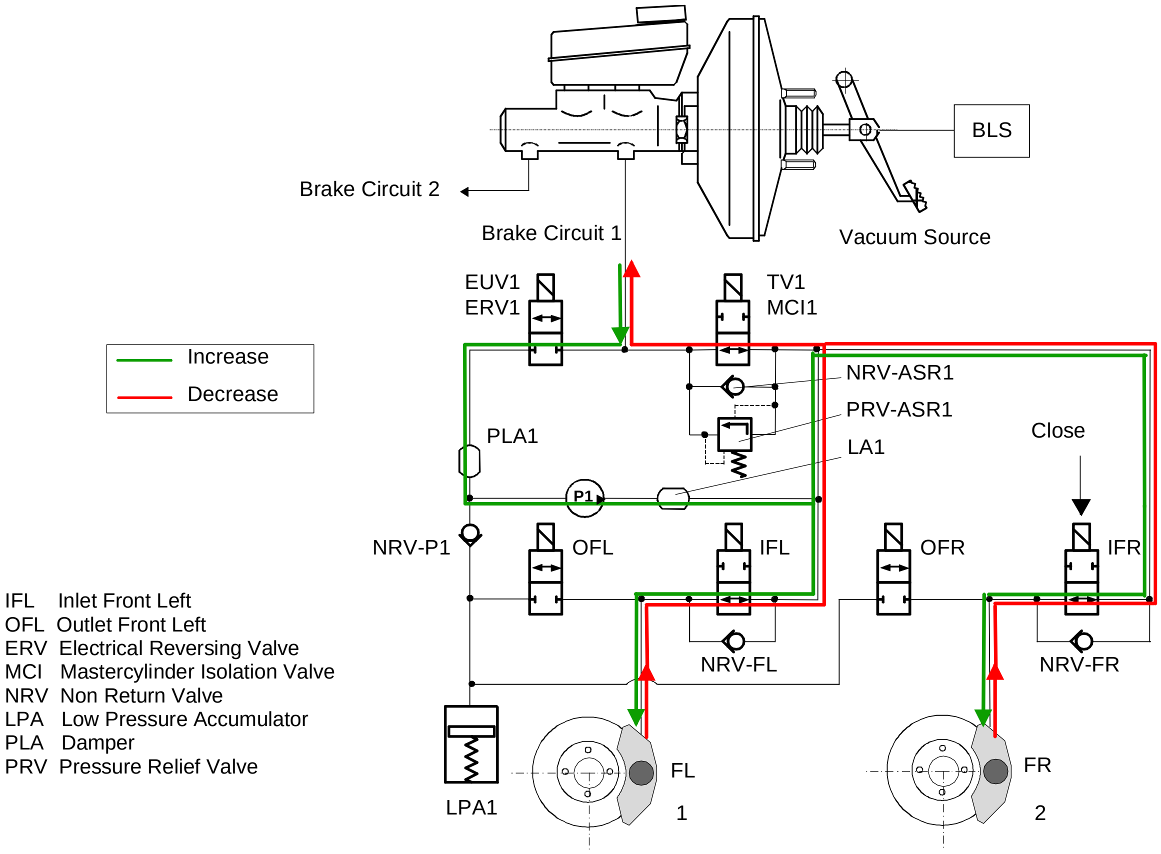


Figure 1: Volume flow during pressure control in one hydraulic circuit

(General schematic, does not necessarily reflect all details of actual configuration in specific project.)

2.1.1 Circuit pressure decisions

		Controller reaction
Grad < 0	Mod < Target	Pressure Increase
	Mod = Target	Pressure Hold
	Mod > Target	Pressure Decrease
Grad = 0	Mod < Target	Pressure Hold
	Mod = Target	
	Mod > Target	
Grad > 0	Mod < Target	Pressure Increase
	Mod = Target	Pressure Hold
	Mod > Target	Pressure Decrease

Table 1: Circuit Pressure Decisions

Start	**Req_loop_start_cmd**
Target	Max of **Req_target_cmd** of both wheels in circuit
Mod	Max of **AYC_MODEL_WHEEL_PRESSURE** of both wheels in circuit
Grad	Requested gradient

2.1.2 Circuit Pressure **Controller Options**

After the hydraulic circuit pressure calculation the owner (Service_id) of the arbitration winner is determined. If this Service requested special circuit pressure controller options and modes these options and modes will be passed to the controller.

OPTIONS:

MCI	On/Off switch for the MCI valves (Possibility to avoid MCI activations).
LPF	On/Off switch for the LPF valves (Possibility to avoid LPF activations).
PUMP	On/Off switch for the pump (Possibility to avoid pump activations).
QUICK_RESPONSE	affects max. demanded press. decrease for current calculation per time
LOW_RAMP	reduces height of ramp – fast transition closed valve → proportional mode
LOW_HYSTERESIS	Between opening and closing valve
MCI_OVERFLOW	keeps MCI valve only partially closed (e.g. acc w/o pressure sensors)
EVAL_GRADIENTS	Evaluate even gradients for controlling valve
ACTIVATE_ANTIPLOPP	this feature enables slower gradients for rising p_{main} (e.g. ohb)
NO_OVERSHOOT	prevents overshooting during pressure increase
NO_UNDERSHOOT	prevents undershooting during pressure decrease
LOW_PRES_EXIT_RAMP	Activate slow exit ramps for mci valve
NOISE_OPT_PUMP_CTRL	Noise optimized pump control
FULL_PUMP_SPEED	forces maximum pump speed if requested gradient is bigger than 500bar/s

Table 2: Circuit Pressure Control Options

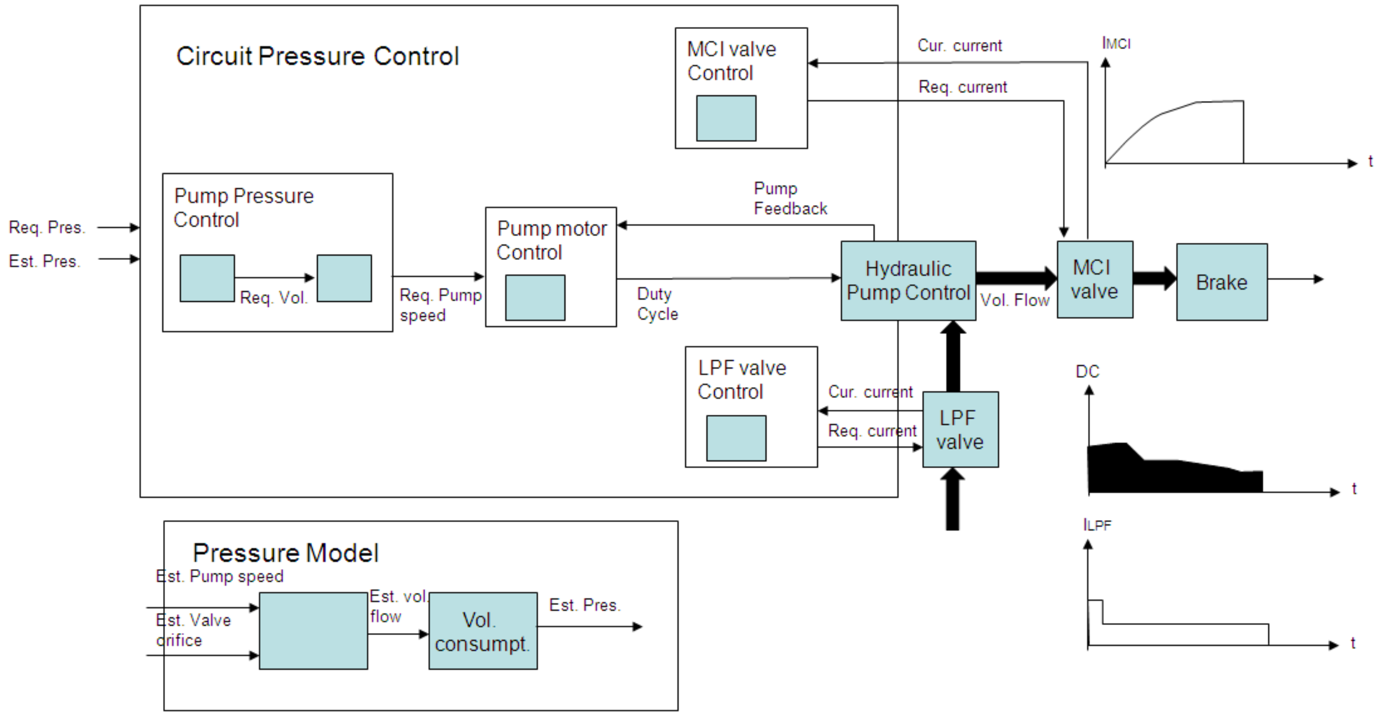
MODES:

Circ_normal_mode	normal mode
Circ_equalization_mode	Mode for pressure equalization after pump run
Circ_backpressure_mode	pump is running, LPF and MCI valve are open
Circ_mci_val_curr_mode	external MCI valve current has to be set
Circ_mci_high_dbv_mode	Higher MCI valve dbv current is possible
Circ_suppr_lpa_pu_mode	Suppress pump control during booster test pulse

Table 3: Circuit Pressure Control Modes

2.2 Volumetric Pressure Control

The following figure illustrates the control circuit:



The control is done by the following components:

- Pump Pressure Control
- MCI Valve Pressure Control
- LPF Valve Pressure Control

The control algorithms are described in the following chapters.

2.2.1 Master Cylinder Isolation Valve Control

The control of the MCI valves (master cylinder isolation valves) is based on controlling the volume flow in the circuit. Each circuit contains two wheels. The volume control for the MCI circuits is active when:

→ (requested pressure > pressure main cylinder)

AND

→ (wheel is not in the wheel pressure control)

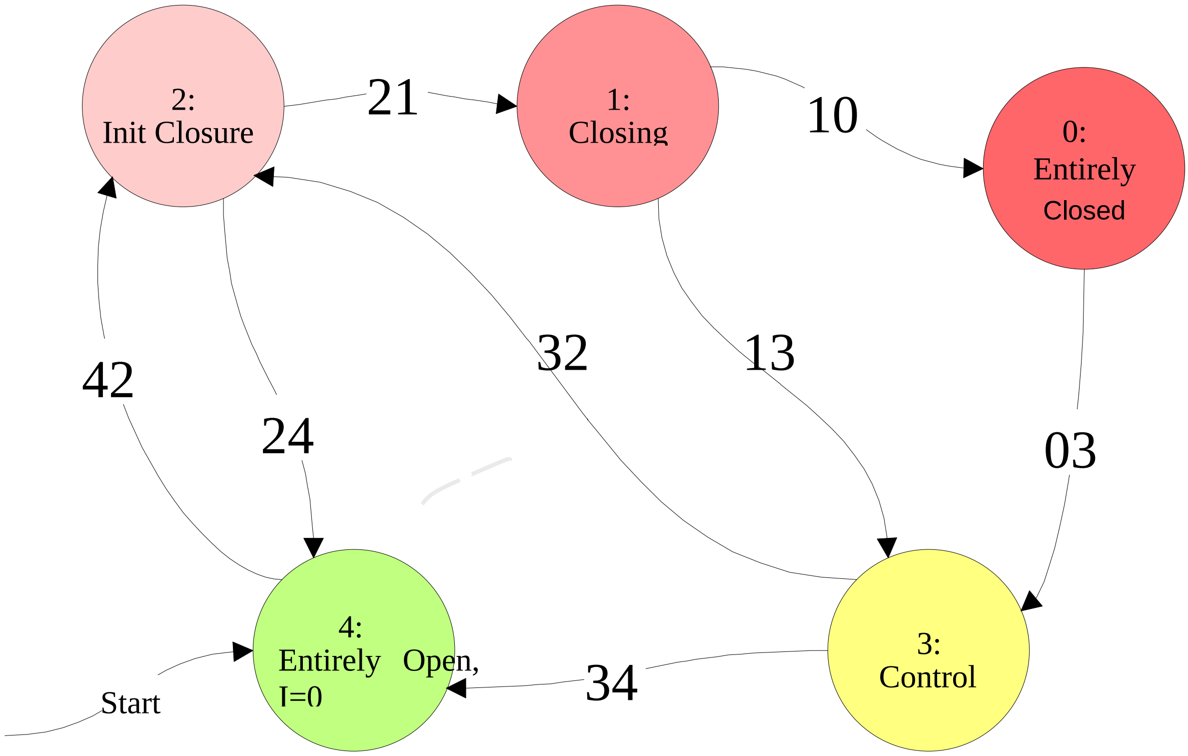


Figure 2: MCI Valve Control State Machine

The states are:

Entirely Open:	Current ramps towards current = 0 A
Init Closure:	Begin of closing procedure, current = f(P_valve + 30 bars)
Closing:	Closing ramp in pressure steps of (12 or 80[*]) bars
Entirely Closed:	Valve Current according to relief pressure
Control:	Valve in proportional mode, partially open

Table 4: MCI State Machine States

The transition conditions are:

Label	*Transition*	*Conditions for Transition*
10	Closing to Entirely Closed	Requested Current > Pressure Relief Current
21	Init Closure to Closing	Req. Pressure > (Pressure Main Cylinder + Control to open offset) [†]
32, 42	Control to Init Closure and Entirely closed to Init Closure	Req. Pressure > (Pressure Main Cylinder + Control to open offset) [2] AND Pressure Main Cylinder < (Model Pressure + Pc_mciv_deltap_close) [‡]
03, 13	Closing or Entirely Closed to Control	Req. Pressure < Model Pressure - CLOS_TO_PROP_OFFSET[1][§] OR Requested Pressure < CTRL_TO_OPEN_OFFSET[2] OR Req. Pressure < (Pressure Main Cylinder + Control to open offset) [2]
24, 34	Init Closure or Control to Entirely Open	Req. Pressure > (Pressure Main Cylinder + OHB Control to open offset) [2] OR Requested Pressure == 0

Table 5: MCI State Transition Conditions

[*] 80 bars when Flag "NO_OVERSHOOT/NO_UNDERSHOOT" is set

[†] controlled by flag: "LOW_HYSTERESIS"; 1 or 3 bars

[‡] leave valve open when pressure increase is done faster by main cylinder

[§] controlled by flag: "NO_OVER_SHOOT/NO_UNDERSHOOT"

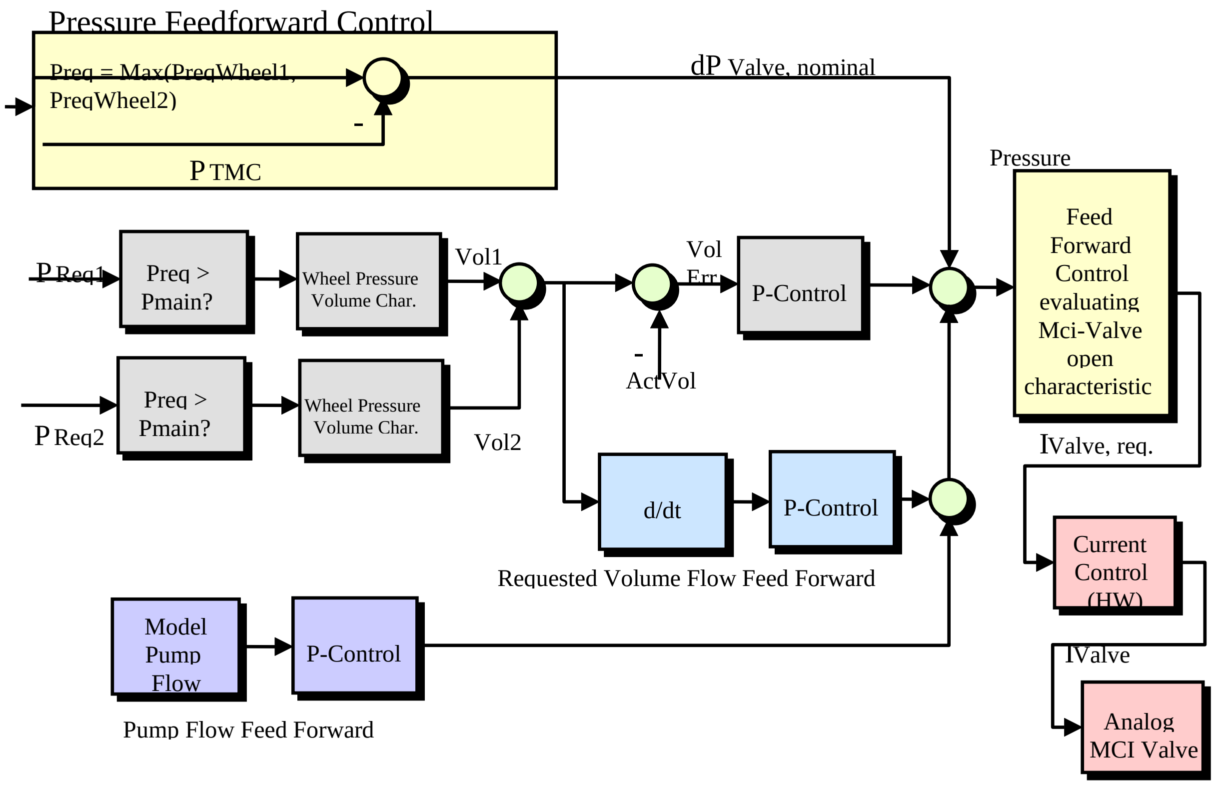


Figure 3: Structure of Volume Control

P-Control

- Proportional Control Block, input is amplified by a factor

Feed Forward Volume Control

- Use the difference of *last requested* volume and actual requested volume
- Open the valve in a way that x% of this volume will flow in e.g. one loop through Mci valve
- Mci_pc_volumebased_p_factor in block P-Control

Volume Control

- Use the difference of *actual* volume and actual requested volume, i.e. actual volume error
- Open the valve in a way that y% of this volume will flow in e.g. one loop through Mci valve
- Mci_pc_volumegradient_factor in block P-Control

Pump Flow Feed Forward

- Model pump flow is multiplied by Mci_pump_overflow_factor in block P-Control

Wheel Volume-Pressure Characteristics

- project dependent parameter array e.g.:

```
extern const signed_int16_t PM_PV_CURVE_P_TAB[10];
/*  0, 500, 1000, 1500, 2000, 2500, 4000, 6000, 8000, 32700, */
#define Pm_pv_curve_p_tab                 PM_PV_CURVE_P_TAB
extern const signed_int16_t PM_PV_CURVE_V_TAB_F[10];
/*  0, 1400, 2600, 3700, 4600, 5500, 7400, 9450, 11400, 32750, */
#define Pm_pv_curve_v_tab_f               PM_PV_CURVE_V_TAB_F


extern const signed_int16_t PM_PV_CURVE_V_TAB_R[10];
/*  0, 1000, 1500, 1900, 2250, 2600, 3500, 4650, 5850, 20400, */
#define Pm_pv_curve_v_tab_r               PM_PV_CURVE_V_TAB_R
```

d/dt

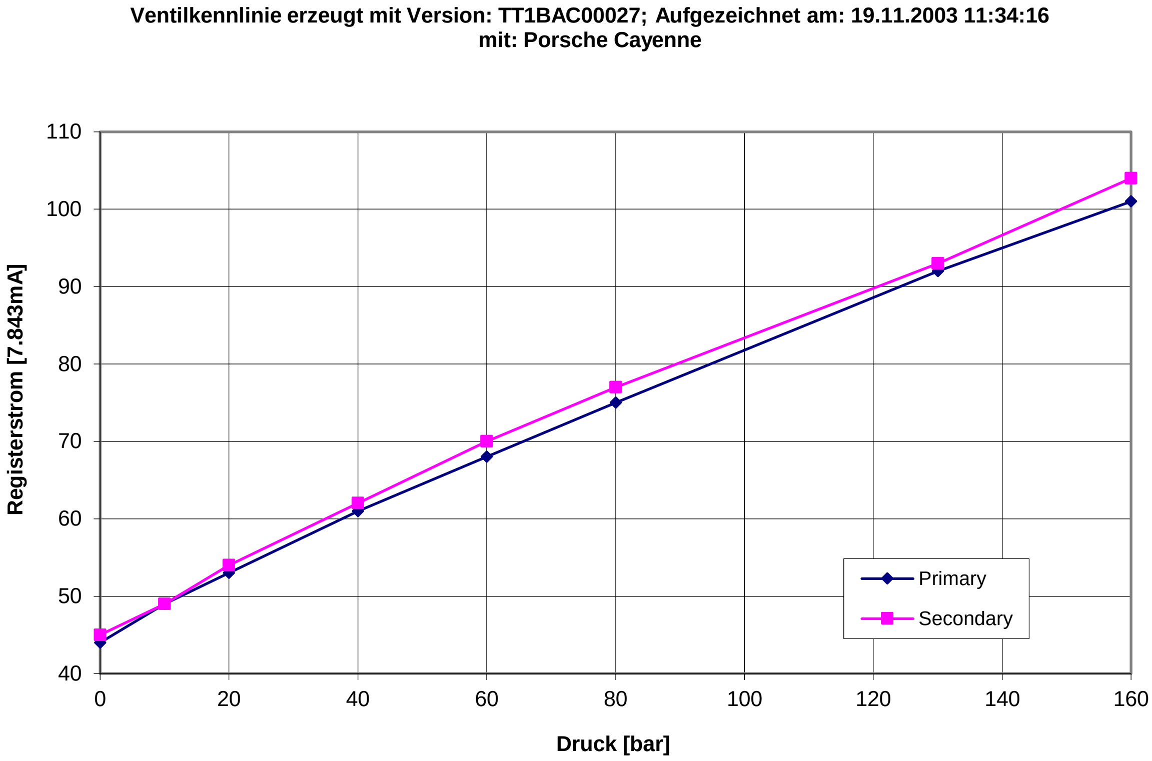
- gradient calculation

Feed Forward Control Evaluating Mci Open Valve Characteristic

- Mci valve open characteristic gives relation between valve pressure and current

More Details can be found here.

Figure 1 Example of Mci Valve Characteristic



2.2.2 LPF valve control

The LPF valve activation is individual in each hydraulic circuit. The LPF valve control for each brake circuit can be described as state machine with the states OPEN (i.e. LPF valve actuated) and CLOSED (i.e. LPF valve not actuated).

The LPF valve control follows the following conditions:

Conditions for potential LPF valve opening	Label
Pump activated following conditions but not for MCI valve pressure limiting function purposes AND set pressure in the considered brake circuit not reached yet (delta > ***pc_increase_thr_out***).	OPEN_BY_PRES_INC_REQ
Brake circuit equalisation active	OPEN_BY_EQU
Back pressure mode active	OPEN_BY_BACKPRES
Positive pressure request and increasing pressure gradient	OPEN_BY_POS_GRD
Pressure control option “ACTIVATE_ANTIPLOPP”	OPEN_BY_ANTIPLOPP
Pressure control option “PERMANENT_OVERFLOW”	OPEN_BY PERM_OFL
Minimum LPF valve actuation time for comfort functions not expired yet	OPEN_BY_POSTRUN

Table 6: LPF valve conditions for valve opening

Conditions for potential LPF valve closing	Label
Pump activated due to pressure increase in the other brake circuit AND requested pressure gradient < 15bar/s AND requested pressures between the brake circuits higher than ***pc_increase_thr_out***	CLOSE_BY_CIRC_PROT
The critical volume of **LPA** is reached OR The LPA shall be emptied OR Both wheels are in wheel individual control AND (**P**$_{CMD}$ >1,2 * **BlockingPressure)**)	CLOSE_BY_LPA
Pressure control option “NO_OVERSHOOT” AND the requested volume delta (dV$_{REQ}$) is bigger than available volume in LPD (space between pump and LPF valve)	CLOSE_BY_NO_OVERSHOOT
Pressure control option “LPF_SWITCH” is not set	CLOSE_BY_LPF_SWITCH
The requested pressure is reached (**P**$_{CMD}$ <= **P**$_{TMC}$ +,***pc_increase_thr_out***) AND the pump is switched off AND no comfort function is active.	CLOSE_BY_NO_REQUEST

Table 7: LPF valve conditions for valve closing

Transition from CLOSED to OPEN:

- OPEN_BY_EQU
- OR OPEN_BY_BACKPRES

- OR OPEN_BY_POS_GRD
- OR OPEN_BY_ANTIPLOPP
- OR OPEN_BY PERM_OFL
- OR OPEN_BY_POSTRUN
- AND NOR CLOSE_BY_CIRC_PROT NOR CLOSE_BY_LPA NOR CLOSE_BY_CIRC_PROT

Transition to OPEN to CLOSED:

- CLOSE_BY_LPA
- OR CLOSE_BY_NO_OVERSHOOT
- OR CLOSE_BY_NO_REQUEST
- OR CLOSE_BY_CIRC_PROT
- AND Minimum LPF valve actuation time for comfort functions has expired AND Brake circuit equalisation finished

Note:

The minimum activation time of the LPF valve for comfort function is 1s beginning at the end of the brake pressure apply.

P_{TMC} : Pressure in tandem master cylinder

P_{CMD} : Maximum pressure request in hydraulic circuit

LPA : Low Pressure Accumulator

LPD : Low Pressure Damper

BlockingPressure : Maximum brake pressure due to actual road friction

***pc_increase_thr_out*:** pressure threshold for control deactivation (see chapter Activation/deactivation threshold for pump pressure control for volumetric pressure control)

2.2.3 Pump pressure control

In the pump pressure control component the pump set speed is generated. There are 2 strategies; gradient based volumetric pressure control using pressure sensors and standard volumetric pressure control (that is currently used only for OHBV).

These strategies are described in the following chapters.

2.2.3.1 Activation/deactivation conditions for pump pressure control for volumetric pressure control

As a precondition of the volumetric pump pressure control some conditions must be fulfilled.

Pump control becomes active if:

- **(P_{CMD} > (P_{TMC}** + ***pc_increase_thr_in))***
- AND (requested pressure delta > ***pc_increase_thr_in)***
- AND **(P_{TMC} < (Maximum brake pressure** + 5 bar***))*** AND the MCI valve is at least partially closed (ASAP: PCMCIVALTI%i > 0)

Pump control becomes inactive if:

- (requested pressure delta < ***pc_increase_thr_out)*** OR **(P_{CMD} < (P_{TMC}** + ***pc_increase_thr_out))***

ASAP: PUMPCSTATE (Pc_pump_ctrl_state_hold, = -1, Pc_pump_ctrl_state_increase_pc = 0, Pc_pump_ctrl_state_increase_sc = 1)

P_{TMC} : Pressure in tandem master cylinder (ASAP: PM_P_TMCFS%i)
P_{CMD} : Maximum pressure request in hydraulic circuit (ASAP: PCCIRCPCMD%i)

Option	Thresholds
ASAP: CO_L_Hys%i	**pc_increase_thr** 0.5bar **pc_increase_thr_out** 0.2bar
ASAP: CO_LEAK_COMP%i	**pc_increase_thr** 1bar **pc_increase_thr_out** 0.5bar
Default	**pc_increase_thr** 3bar **pc_increase_thr_out** 1.5bar

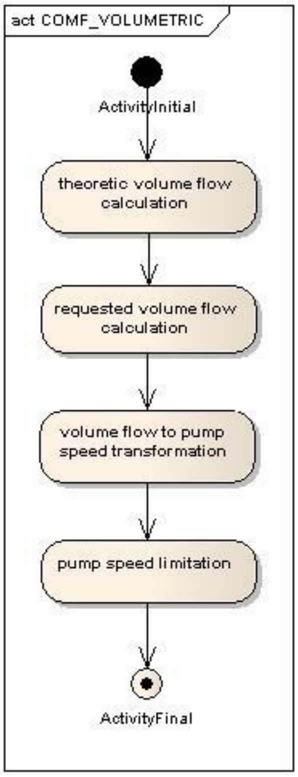
pc_increase_thr : pressure increase threshold

pc_increase_thr_out : pressure increase leaving threshold

2.2.3.2 Gradient based volumetric pressure control using pressure sensors

The algorithm for gradient based volumetric pressure control using pressure sensors is executed in case that a minimum control deviation is present (see chapter above).

If the minimum control deviation is detected the algorithm illustrated in the following figure is executed.



Theoretic volume flow calculation

The theoretic volume flow calculation calculates the necessary volume flow to apply the requested pressure gradient. Besides the volume error is calculated considering the different pV characteristics of the wheel brake calipers.

Input:

Requested pressure (ASAP: PCCIRCPREQ%i)

Current volume of the wheel brake calipers (ASAP: PM_WHVOL_%w)

Output:

Requested volume flow (ASAP: PCCIRCREQVOLFLOW%i)
Total volume error (ASAP: PCCIRCVREQ%i)
Auxiliary output:
Filtered requested pressure gradient (PCCIRCGRADPFIL%i)

Requested volume flow calculation

The theoretic volume flow calculation adds a portion of the total volume error to the theoretical requested volume flow.

Note:

- Small pressure control errors are suppressed for NVH reasons
- In case of negative control errors a minimum requested volume flow is requested for NVH reasons.

Input:

Requested volume flow (ASAP: PCCIRCREQVOLFLOW%i)
Total volume error (ASAP: PCCIRCVREQ%i)

Output:

Requested volume flow

Volume flow to pump speed transformation

The volume flow to pump speed transformation transforms the requested volume flow into a pump speed considering the pump feed characteristic.

Input:

Requested volume flow

Output:

Requested pump speed (ASAP:PUMPREQ)

Pump speed limitation

The pump speed limitation limits the level and the gradient of the requested pump speed. If the level exceeds a pressure gradient dependent level (Pc_pump_overflow_speed_limits) the pump speed is limited to the specified level. If the pump speed is increasing the requested pump speed is filtered (time constant: Pc_pump_overflow_speed_fil_cons/2)

Input:

Requested volume flow
Filtered requested pressure gradient (PCCIRCGRADPFIL%i)

Output:

Requested pump speed (ASAP:PUMPREQ)

2.2.3.3 Standard volumetric pressure control

In standard volumetric pressure control the pump speed is requested depending on the maximum volume request of both hydraulic circuits.

For the activation of the pump pressure controller the activation conditions have to be fulfilled.

Necessary pump speed is determined using a kind of PID controller. Due to different requested modes and options the pump request is calculated in different ways:

Condition	Pump request =

"Normal control" during **ACTIVE** State	**(Pvalue + Dvalue + Ivalue)** **Pvalue** see sub conditions **Dvalue = (dV_{REQ} - dV_{REQ}LastLoop) *** ***Pump_d_fac*** (if **$dP_{REQ,max}$** >0) **Ivalue** is only increased if volume deviation stays constant. Due to this Ivalue is incremented after every 80ms if volume change is smaller them 0.025ccm/10ms. If the change rate is higher than 0.025ccm/10ms the **Ivalue** is decreased with double speed.
"Normal control" during **ACTIVE** State	**Pvalue = $dV_{REQ,max}$ *** ***Pump_p_fac***
"Normal control" during **ACTIVE** State AND option "ACTIVATE_ANTIPLOPP"	**Pvalue = dP_{REQ} *** ***Pump_p_fac*** (if **$dV_{REQ,max}$** >0.025ccm)

Condition	PID parameter
option "LEAKAGE_COMPENSATION"	***Pump_p_fac*** = 25 ***Pump_d_fac*** = 0
option "ACTIVATE_ANTIPLOPP"	***Pump_p_fac*** = 25 ***Pump_d_fac*** = 0
Default	***Pump_p_fac*** = 75 ***Pump_d_fac*** = 0

dV_{REQ} : Requested volume delta in circuit
(derived from actual wheel pressures, requested pressures and pV- curves)

$dV_{REQ,max}$: Maximum of the volume deltas of the brake circuit

dP_{REQ} : Pressure delta in the pump controller circuit

2.2.4 Pump motor control

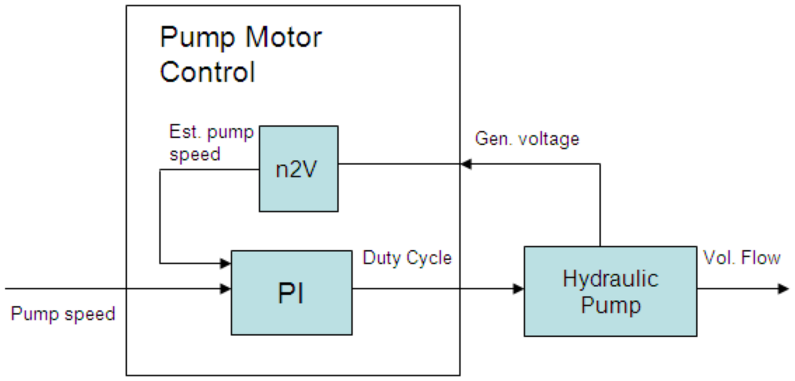
The above calculated pump request is controlled according to the specified pump motor control strategy. The following pump motor control strategies are available:

- Closed loop pump voltage control (using the pump motor generator voltage)
- Open loop pump voltage control (using a fixed characteristic)
- Closed loop pump voltage control (using the pump position sensor)

The different control strategies are illustrated in the following chapters.

2.2.4.1 Closed loop pump voltage control

The following figure illustrates the control circuit.

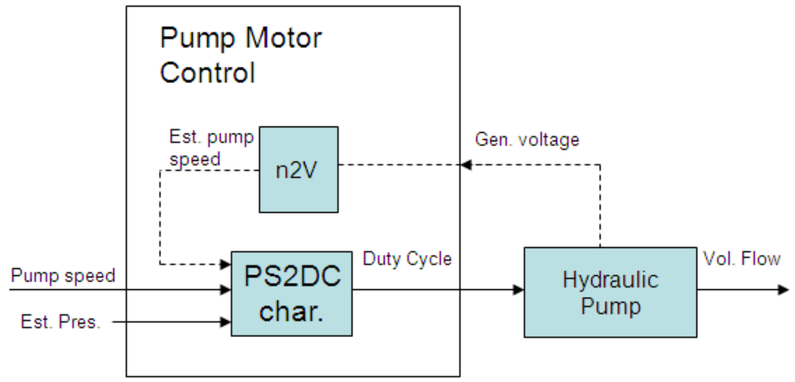


The requested pump speed is transformed into a voltage. The voltage is transformed into a duty cycle that is applied by the pump motor driver.
The generator voltage in pump off state is used as feedback channel.

Input:
Requested pump speed (ASAP: PMPMTRCTRL_CMD)
Generator voltage (ASAP: PMPMTRCTRL_AVG_VOLTAGE)
Output:
Requested duty cycle (ASAP: PMPMTRCTRL_DC_CMD)

2.2.4.2 Open loop pump voltage control

The following figure illustrates the control circuit.



The requested pump speed is transformed into a duty cycle considering the load of the pump. The duty cycle is applied by the pump motor driver. The driver executes a hardware PWM of 18kHz.

The generator voltage in pump off state is used as feedback channel each 100ms.

Input:

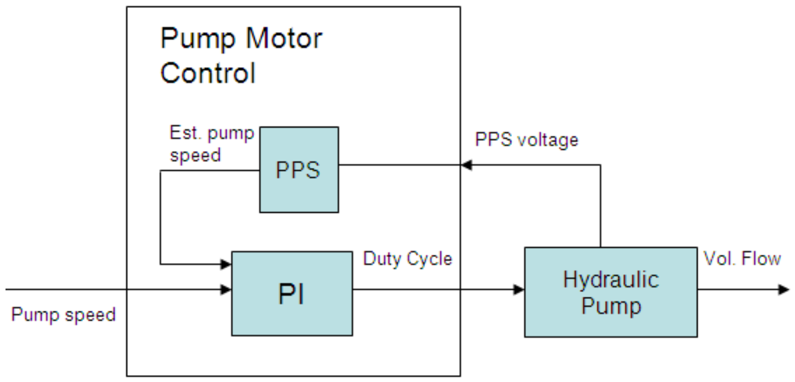
Requested pump speed (ASAP: PMPMTRCTRL_CMD)
Generator voltage (ASAP: PMPMTRCTRL_AVG_VOLTAGE)

Output:

Requested duty cycle (ASAP: PMPMTRCTRL_DC_CMD)

2.2.4.3 Closed loop pump speed control

The following figure illustrates the control circuit.



The requested pump speed is transformed into a duty cycle that is applied by the pump motor driver. The driver executes generally a hardware PWM of 18kHz.

The pump speed signal generated by the PPS is used as feedback channel.

Input:

Requested pump speed (ASAP: PMPMTRCTRL_CMD)
Current pump speed (ASAP: PPS_RPM)

Output:

Requested duty cycle (ASAP: PMPMTRCTRL_DC_CMD)

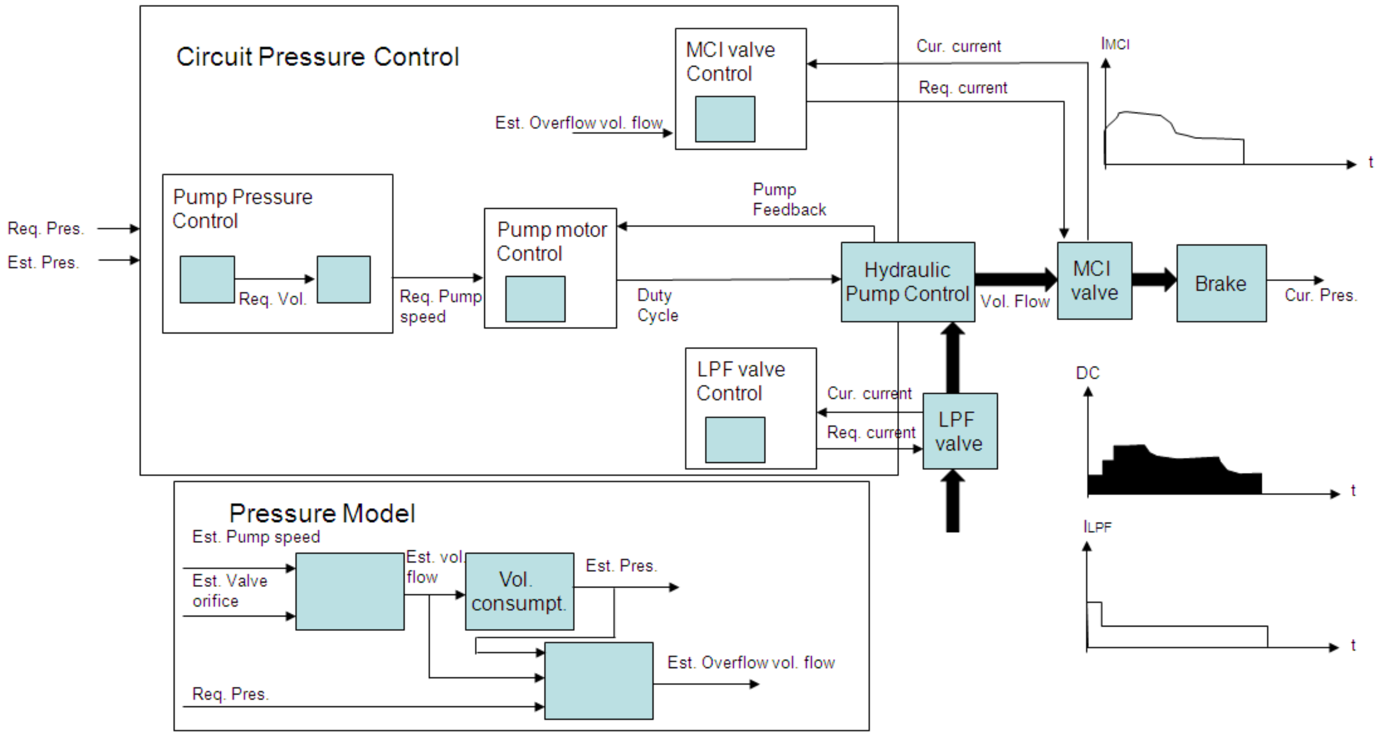
#if (OVERFLOW)

2.3 Overflow

Overflow pressure control is used to improve pressure accuracy.
It needs special hardware (e.g. optimized TCS valve (MCI valve))
So it is only available in MkxxA, MkxxE1optimized and MK100 systems.

Whereas in MkxxE1optimized system overflow control is only used during ACC control, it is used in general in MkxxA and MK100 systems (e.g. also during AYC/BTCS/…)

The following figure illustrates the control circuit:

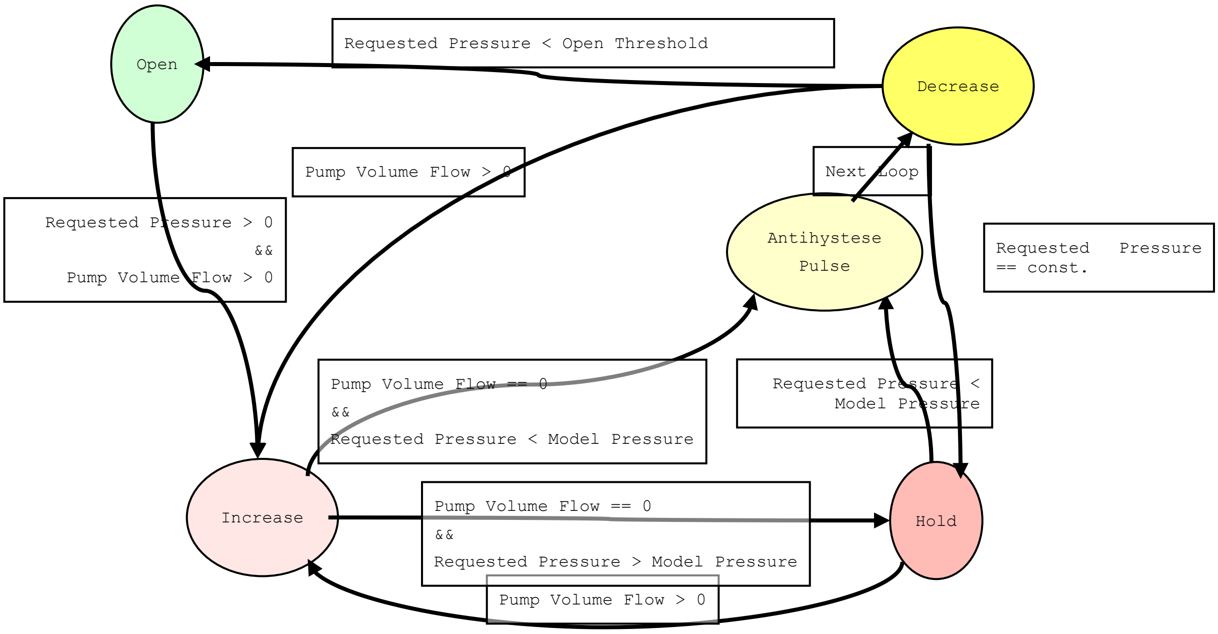


The control is done by the following components:

- Pump Pressure Control
- MCI Valve Pressure Control
- LPF Valve Pressure Control

The control algorithms are described in the following chapters.

2.3.1 States of MCI-Valve Control in Overflow Mode



2.3.1.1 Without Pressure Sensors

- **Open:** I = 0
- **Increase:** I = f(Requested Pressure**1**) + 50 mA

GET_MCI_LOW_PRESS_OVERFLOW_DP(pressure, temperature, volumeflow)(future)

- **Decrease:** I = f(Requested Pressure**1**) + LOW_GRADIENT_FEATURE_PRESSURE
- **Hold:** I = f(Requested Pressure**1**) + Mci_acc_corr_ramp_height (~10 bar)

1) f(Requested Pressure) = Open Current Characteristic

2.3.1.2 Pressure sensors available

- **Open:** I = 0
- **Increase:** I = f(Requested Pressure**1**) + 50 mA + **PI-control2**)
- **Decrease:** I = f(Requested Pressure**1**) + E5-like volume error based control,
- **Hold:** I = f(Requested Pressure**1**) + Mci_acc_corr_ramp_height (~10 bar)

f(Requested Pressure) = Open Current Characteristic

Based on stepwise increasing filtered wheel pressure: next step is next local minimum of pressure signal

Low Gradient Feature – time on open characteristic

```
**--------------------------------------------------------------------**

 **                  assuming  Hagen-Poiseuille  law:                                                  **
 **                                                                                                    **
 **               dV     Pi  *  R²  *  R²  *  dP                                                       **
 **                --  =  -----------------                                                            **
 **               dt        8  *  Eta  *  L                                                            **
 **                                                                                                    **
 **               where                                                                                **
 **                       V   is   a   volume   of   the   liquid,   poured   in   the   time   unit   t,   **
 **                 R  the  internal  radius  of  the  tube,                                           **
 **                     P  the  pressure  difference  between  the  two  ends,                        **
 **                 Eta  the  dynamic  fluid  viscosity  and                                           **
 **                L  the  total  length  of  the  tube                                                **
 **                                                                                                    **
 **                 ignoring  influence  of  L  and  Eta:                                              **
 **                                                                                                    **
 **        dV/dt = const * dP ->                          **

 **               dt  =  dV/dP  *  ~const                                                              **
 **                                                                                                    **
 **                      influence  of  L  is  mirrored  in  one  const  for  each  circuit  **
 **--------------------------------------------------------------------*/
```

- ***Mci_lgf_exit_press_threshold***: below this pressure, no LGF is done.
- ***Mci_lgf_no_of_loops_low***: No of loops on open current characteristic in LGF
- ***Mci_lgf_primary/secondary_factor***: No of Loops on Open Current Characteristic is proportional to this factor and quotient VolFlow/Press, i.e. of requested filtered volume flow and pressure with regard to hydraulic circuit
- ***Mci_lgf_step_height***: height of pressure steps when in ramps in or out of LGF

2.3.1.3 Actions on Transitions

- **Transition into Increase**
  - „1 Millisecond 0 mA-needle“ during 1st loop with **I = I(requested pressure) + Overflow Offset AND sufficient pump volume flow** for remaining loop time. **Alternatively 2 ms 200 mA below model pressure for model pressures above 30 bars**
  - Walk around hysteresis curve to get into working point, i.e. lower side of hysteresis.
  - No hydraulic response due to very short „open“ time.
- **Transition into Decrease and Hold**
  - High current close pulse with **I = I(Pmax)** (*MCI_IOUT00/01*)for whole 1st loop (10 ms).

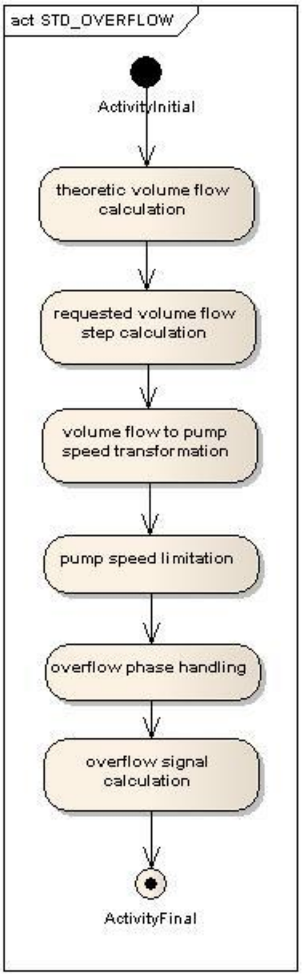
  - Walk around hysteresis curve to get into working point, i.e. upper side of hysteresis or open current characteristic
  - Little delay
- **Transition into Open**
  - To be defined Negative requested pressures or fix exit ramp
  - Hide tolerances of MCI-valve system

2.3.2 LPF Valve Control

See chapter LPF valve control (in the chapter Volumetric Pressure Control).

2.3.3 Pump pressure control

The following figure illustrates the algorithm.



Theoretic volume flow calculation

The theoretic volume flow calculation calculates the necessary volume flow to apply the requested pressure gradient. Besides the volume error is calculated considering the different pV characteristics of the wheel brake calipers.

Input:

Requested pressure (ASAP: PCCIRCPREQ%i)

Current volume of the wheel brake calipers (ASAP: PM_WHVOL_%w)

Output:

Requested volume flow (ASAP: PCCIRCREQVOLFLOW%i)
Total volume error (ASAP: PCCIRCVREQ%i)
Auxiliary output:
Filtered requested pressure gradient (PCCIRCGRADPFIL%i)

Requested volume flow step calculation

The theoretic volume flow step calculation adds a portion of the total volume error to the theoretical requested volume flow and adds the minimum requested overflow volume flow (*Pc_pump_flow_min_mci_overflow*).

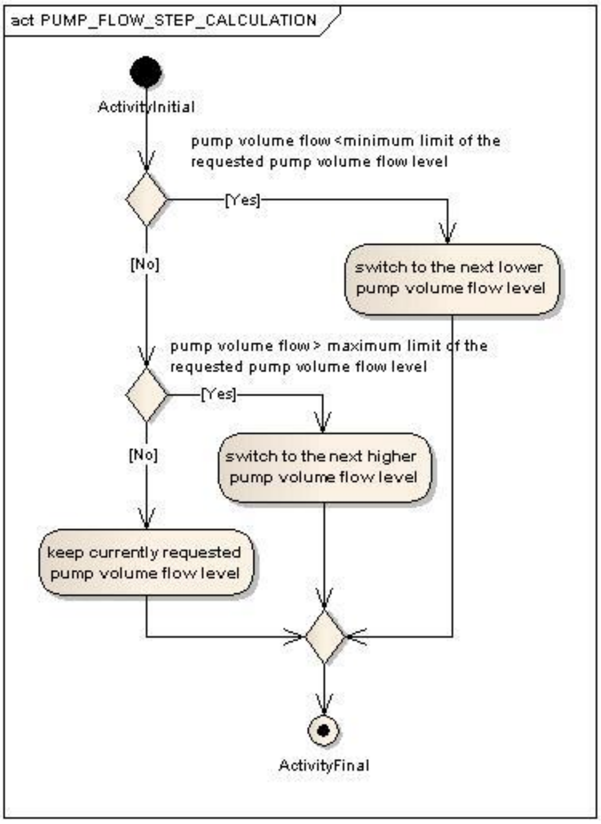
Note:

- Small pressure control errors are suppressed for NVH reasons
- In case of negative control errors a minimum requested volume flow is requested for NVH reasons.

The resulting volume flow is divided into steps of volume flow. The permitted steps are calculated according to the following equation:

vol_flow_step = *Pc_pump_flow_thr_mci_overflow* x n, where n is an integer.

The decision what step to choose is done according to the following algorithm:



The switching between the different levels is done evaluating a threshold (*Mci_overflow_flow_hys*/2) and a time criterion. Changes of the requested volume step can only happen each *Pc_pump_overflow_idx_delay_time.*
Note:
In case that full pump speed is needed (ASAP: PUMPOFLCFULLPS, or CO_MAX_PINC%i) the requested volume flow step is directly applied.

Input:

Requested volume flow (ASAP: PCCIRCREQVOLFLOW%i)
Total volume error (ASAP: PCCIRCVREQ%i)

Output:

Requested volume flow step (ASAP: PUMPOFLREQIDX)

Volume flow to pump speed transformation

The volume flow to pump speed transformation transforms the requested volume flow into a pump speed considering the pump feed characteristic.

Input:

Requested volume flow

Output:

Requested pump speed (ASAP:PUMPREQ)

Pump speed limitation

The pump speed limitation limits the level and the gradient of the requested pump speed. If the level is higher a pressure gradient dependent level (*Pc_pump_overflow_speed_limits*) the pump speed is limited to the specified level. If the pump speed is decreasing the requested pump speed is filtered (time constant: *Pc_pump_overflow_speed_fil_cons*/2)

Input:

Requested volume flow
Filtered requested pressure gradient (PCCIRCGRADPFIL%i)

Output:

Requested pump speed (ASAP:PUMPREQ)

Overflow phase handling

In overflow phase handling the timer assuring the minimum overflow time (*Pc_pump_overflow_min_act_time*) is set and decremented. Besides a specified post run is assured (*Pc_pump_overflow_post_run_time*) and the state while overflow is determined.

Input:

n.a.

Output:

Remaining minimum overflow time (ASAP: PUMPOVERFTIMER)
Overflow state (ASAP: PUMPOFLCSTATE (Pc_pump_overflow_ctrl_inactive= 0, Pc_pump_overflow_ctrl_increase = 1, Pc_pump_overflow_ctrl_postrun = 2)

Overflow signal calculation

In overflow signal calculation a signal signaling MCI valve overflow volume flow is calculated.

Input:

Remaining minimum overflow time (ASAP: PUMPOVERFTIMER)
Current pump flow (ASAP: PMQPUMP%i)

Output:

MCI valve overflow volume flow presence (ASAP: PUMPOFLVOLFLOWP, PUMPOFLVOLFLOWPSC)

2.3.4 Pump motor control

See chapter Pump motor control (in the chapter Volumetric Pressure Control).

```
#endif /*(OVERFLOW)*/
```

3 Wheel Pressure Control

3.1 Wheel Individual Pressure Control

The wheel pressure controller is activated if the wheel pressure is lower than the system pressure (e. g. ABS). The main control structure of the wheel pressure controller is a state machine in the main loop. Depending on the requested wheel pressure gradient and the activation by the pressure arbitration, the state of the pressure controller is set (***Pctrl_passive, Pctrl_hold, Pctrl_increase, Pctrl_decrease***). If the wheel pressure controller is in the pressure increase phase, the analogue inlet valves are opened by using the valve current controller, where they are controlled in a 5ms sub-cycle-loop. During a pressure decrease phase, the inlet valves are closed and the outlet valves are opened.

3.2 Wheel Pressure Control Decisions

<table>
<tr><th colspan="2"></th><th>Start < Target</th><th>Start = Target</th><th>Start > Target</th></tr>
<tr><td rowspan="3">Grad < 0</td><td>Mod < Target</td><td rowspan="3"></td><td rowspan="3" colspan="2">Pressure Decrease</td></tr>
<tr><td>Mod = Target</td></tr>
<tr><td>Mod > Target</td></tr>
<tr><td rowspan="3">Grad = 0</td><td>Mod < Target</td><td rowspan="3" colspan="3">Pressure Hold</td></tr>
<tr><td>Mod = Target</td></tr>
<tr><td>Mod > Target</td></tr>
<tr><td rowspan="3">Grad > 0</td><td>Mod < Target</td><td colspan="2">Pressure Increase</td><td></td></tr>
<tr><td>Mod = Target</td><td rowspan="2" colspan="2">Pressure Hold</td><td rowspan="2"></td></tr>
<tr><td>Mod > Target</td></tr>
</table>

Table 8: Actuator Interface Wheel Pressure Decisions

Start: **req_loop_start_cmd**
Target **req_target_cmd**
Mod: **WHEEL_DATA_SC[whl_nr].PRESS_EST** (Model pressure or sensor pressure value)
Grad: **reqested_grad**
Incorrect use of the interface (should be avoided)

If the wheel pressure is less than 15 bars or the pressure difference between TMC and wheel is less than 20 bars, the analogue inlet valve function is not ensured.

3.3 Wheel Pressure Control Phases

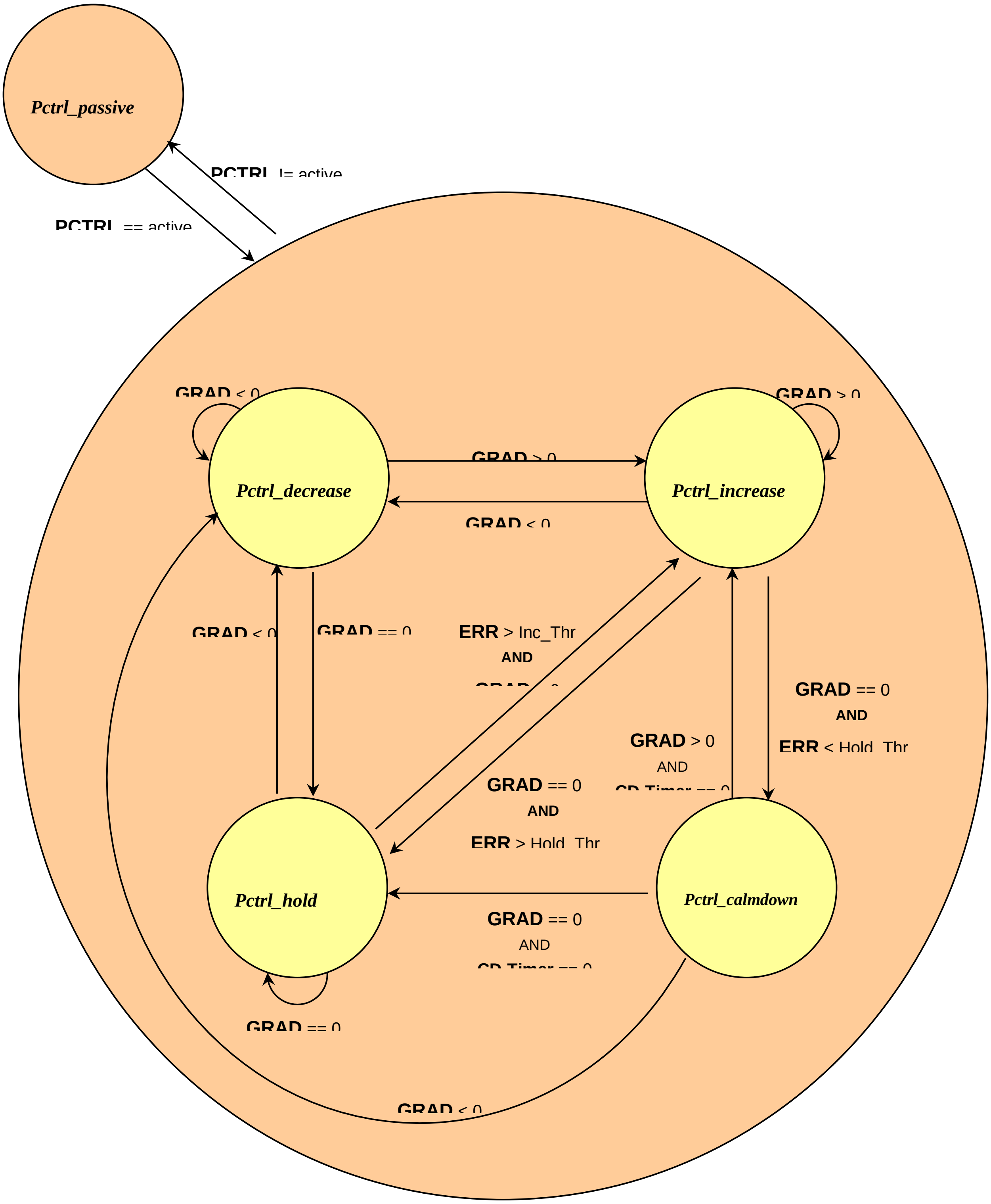


Figure 4: Graphical form of Wheel Pressure Controller State Machine

3.3.1 The Brake States

The diagram (Figure 8) shows the state machine around the wheel pressure controller. The state machine has 5 states:

The state ***Pctrl_passive*** is directly controlled by the arbitration. Thus it is a general switch for the whole wheel pressure controller, which cannot lift itself out of this state or move actively into it.

Pressure decrease ***Pctrl_decrease*** is done by the decrease controller. It is activated solely by a negative pressure gradient.

Pressure increase ***Pctrl_increase*** is calculated by another algorithm, which can force a hold- or calm_down- state and reanimate itself out of this, driven by the control error, Calmdown-Timer (CD-Timer) and the gradient.

In state ***Pctrl_hold*** the outlet- and inlet-valves are closed.

The state ***Pctrl_calmdown*** was created to reduce changes in the state machine (increase – hold –increase) because of pressure oscillations. In this state the inlet valves are closed for 20ms to calm down the measured pressure signal.

The following diagram (Figure 9) shows the wheel pressure state machine in tabular form:

<table>
<tr><th rowspan="3">Actual State</th><th rowspan="3">Timer > 0</th><th colspan="6">Calmdown Timer == 0</th></tr>
<tr><th colspan="3" rowspan="2">ERR < Hold_Thr</th><th rowspan="2">Hold_Thr < ERR < Inc_Thr</th><th colspan="2">ERR > Inc_Thr</th></tr>
<tr><th>Grad > 0</th><th>Grad = 0</th></tr>
<tr><td>HOLD</td><td>CALM</td><td colspan="3">HOLD</td><td>HOLD</td><td>INCREASE</td><td>HOLD</td></tr>
<tr><td>CALM</td><td>CALM</td><td colspan="3">HOLD</td><td>HOLD</td><td>INCREASE</td><td>HOLD</td></tr>
<tr><td rowspan="3">Increase</td><td rowspan="3">CALM</td><td>Last State</td><td>Low Grad</td><td>High Grad</td><td rowspan="2">HOLD</td><td rowspan="3">INCREASE</td><td rowspan="3">HOLD</td></tr>
<tr><td>Calm Hold</td><td>Increase Timer = 5</td><td>Calm_down Timer = 5</td></tr>
<tr><td>Inc</td><td>Calm_down Timer = 5</td><td>Calm_down Timer = 5</td><td>INCREASE</td></tr>
</table>

Figure 5: Tabular form of Wheel Pressure Controller State Machine

3.3.2 The Threshold for State Switch

The switch of states can be influenced by two thresholds for pressure increase and pressure hold:

Pressure hold threshold: Static Threshold (default 1bar) Av_stat_thr_press_hold + Threshold Offset (because of high gradient) + Threshold Offset (because of permanent reduction of pressure error)

Pressure increase threshold: Static threshold (default 4bar) Av_stat_thr_press_increase

If a requested pressure increase is recognized the pressure increase threshold is reduced to the half. The increase threshold is limited to the hold threshold.

3.4 Pressure Decrease

The outlet valves are digital valves. To reach the arbitrated pressure request during a pressure decrease phase, the valve activation time (**valti**) for the digital outlet valves has to be calculated.

For getting a hydraulic reaction, the outlet valve has to be opened for a minimum time. This minimum time results in a minimum pressure decrease pulse which has to be considered by the control functions. In the interface to control functions the following information is included. The control functions must take account of these restrictions.

`Get_max_pres_after_min_dec_pulse(x)`

`Description : returns the maximum wheel pressure after a pressure decrease of the selected wheel channel x (wheel valve control (normally closed valve)); if the pressure request is smaller or equal this value, it is guaranteed that a decrease pulse will be given`

If the resulting valve activation time is negative (which means that the outlet valve will be opened), it is limited to values between (-1)**`*Loop_time_ms`** and a minimum value which depends on the wheel pressure (this is the minimum time for getting a hydraulic reaction).

The different states of the wheel individual pressure decrease control are described here:

3.4.1 No_activation

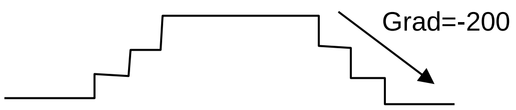
If the requested pressure gradient `WHEEL_DATA_MC[wh_nr].PRESS_GRAD` is positive or if the requested pressure gradient is zero and the requested pressure `WHEEL_ACT_CMD_PTR[wh_nr]->REQ_NEXT_CMD` is not zero, then the outlet valve remains in normal state (no activation, valve is closed).

3.4.2 Unpulsed_to_zero

If the requested pressure gradient `WHEEL_DATA_MC[wh_nr].PRESS_GRAD` is negative and the actual pressure request `WHEEL_ACT_CMD_PTR[wh_nr]->REQ_NEXT_CMD` is zero, the outlet valve is opened for the whole loop.

3.4.3 Closed_loop_pdec

If the requested pressure gradient `WHEEL_DATA_MC[wh_nr].PRESS_GRAD` is negative and the actual pressure request `REQ_CMD_END_VALUE[wh_nr]` (`=AYC_MODEL_WHEEL_PRESSURE[wh_nr] + WHEEL_DATA_MC[wh_nr].PRESS_GRAD`) is greater than zero the closed loop pressure decrease mode is set. The valve activation depends on the difference between the actual model wheel pressure `AYC_MODEL_WHEEL_PRESSURE[wh_nr]` and the actual pressure request `REQ_CMD_END_VALUE[wh_nr]`. A pressure decrease is only performed if the actual pressure request is smaller than the maximum possible wheel pressure `Get_max_pres_after_min_dec_pulse(whl_nr)`.



`#if (MK60E5)`

3.4.4 Open_loop_pdec

This state only exists for MkxxE5 systems (and motor bikes with wheel pressure sensors). During ABS/EBD pressure decrease, the wheel pressure sensor information can not be used for the pressure control because of the sensor signal oscillation. Therefore the valve activation time is calculated by the pressure request change.

If the requested pressure gradient `WHEEL_DATA_MC[wh_nr].PRESS_GRAD` is neagtive and the actual pressure request `WHEEL_ACT_CMD_PTR[wh_nr]->REQ_NEXT_CMD` is greater than zero and the request comes from ABS/EBD, then the open loop pressure decrease mode is set. The valve activation depends on the difference between the actual pressure request and the last pressure request. A pressure decrease is only performed if the actual pressure request is smaller than the maximum possible wheel pressure `Get_max_pres_after_min_dec_pulse(whl_nr)`.

#endif /*(MK60E5)*/

3.4.5 Leakage_protection

If the requested pressure gradient `WHEEL_DATA_MC[wh_nr].PRESS_GRAD` is zero and the actual wheel pressure request `WHEEL_ACT_CMD_PTR[wh_nr]->REQ_NEXT_CMD` is zero, then a pulsed valve activation is started to avoid pressure increase by leakage (during active pressure control on one wheel there can be a pressure increase on the other wheel in this circuit by leakage via the closed inlet valve).

3.5 Pressure Increase

During the pressure increase phase, the analogue inlet valves are opened until the requested wheel pressure is reached. Due to different system configurations (systems with different valves, with/without wheel pressure sensors) there result the following pressure increase modes:

- Analogue closed loop pressure increase (systems with 4 wheel pressure sensors): The analogue inlet valves are opened by using the valve current controller, where they are controlled in a 5ms-sub-cycle-loop. The wheel pressure sensor signals are used to get the the control error for the decision increase-, hold- or calm_down- state (see chapter The Brake States).

- Analogue open loop pressure increase (systems without wheel pressure sensors): The analogue inlet valves are opened by using the valve current controller, where they are controlled in the main loop.

- Digital pressure increase: If the system preconditions for analogue valve control are not reached (e. g. no pressure informations available, digital valves), the valves are opened with full open current 0 mA.

In the following chapters, the calculation of the valve activation time and of the valve current is described for these three modes.

3.5.1 Valve activation time calculation

Analogue closed loop pressure increase:

The analogue inlet valves are opened for the whole time of the 5ms-sub-cycle-loop if the requested wheel pressure is not yet reached. If the requested pressure is reached, the wheel pressure controller phase changes from increase to hold or calm_down and the inlet valve is closed.

Analogue open loop pressure increase:

If the wheel pressure model has not yet reached the requested wheel pressure, the valve time for opening the inlet valve is calculated by the following formula:

$$\frac{P_{req} - P_{\mathrm{mod}}}{Gradient}$$

If the resulting valve activation time is positive and smaller than 10 ms, it is set to 10 ms if the valve was not open the loop before.

Digital pressure increase:

If the wheel pressure model has not yet reached the requested wheel pressure, the valve time for opening the inlet valve is calculated by the following formula:

$$\frac{P_{req} - P_{\mathrm{mod}}}{Gradient}$$

If the resulting valve activation time is positive and smaller than Coa_tpinc_min, it is set to Coa_tpinc_min if the valve was not open the loop before.

3.5.2 Valve current calculation for analogue mode

3.5.2.1 System Pressure

If the MCI valve is open, the system pressure is the difference of twin main cylinder pressure and wheel pressure. If the MCI valve is closed, the maximum of the TMC pressure and of the two wheel pressures of this circuit reflects the system pressure.

3.5.2.2 Pressure Difference on the Inlet Valve

The opening current (I_{open}) of an analogue inlet valve depends on the pressure difference between the system pressure and the wheel. The figure below shows a typical opening current table of two analog inlet valves. The valve characteristic can be different for all 4 wheels. In 5-sensor systems, it is acquired by the valve calibration procedure and stored in the EEPROM, single-sensor systems use default axle individual valve characteristics.

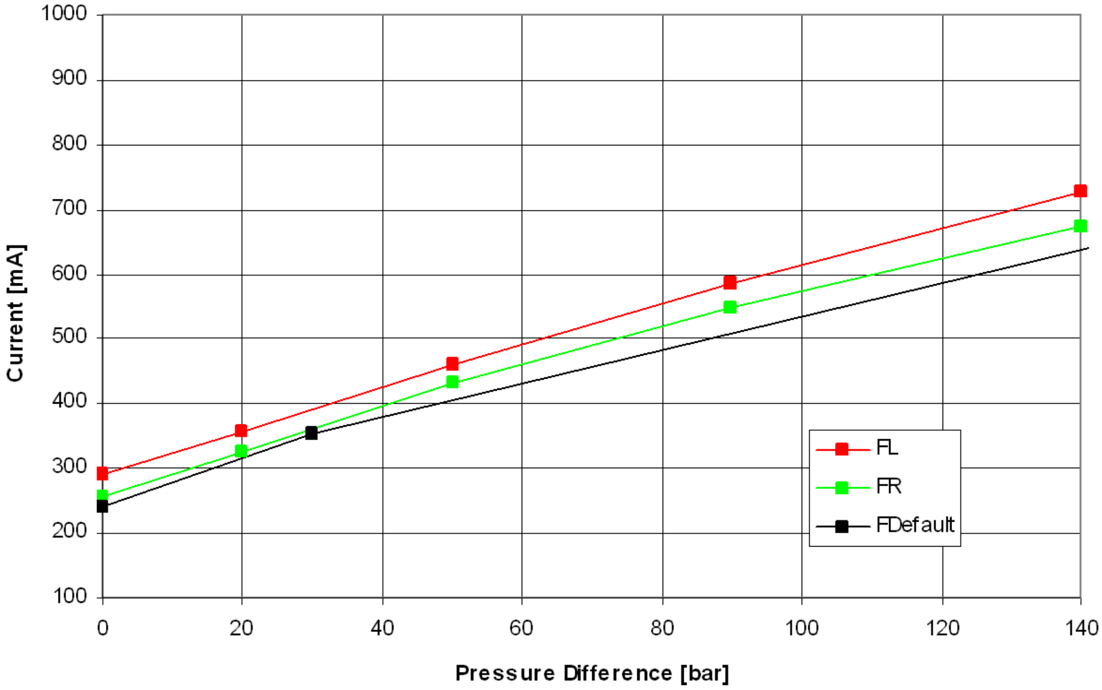


Figure 6: Example of ADNO-Characteristic

According to the design of an analogue inlet valve, it does not use a spring to produce a counter force for position stabilising. It uses the hydraulic flow for stabilization. Obviously, that depends on the pressure difference, which generates the flow.

3.5.2.3 Pressure-Volume-Characteristic and Capacity

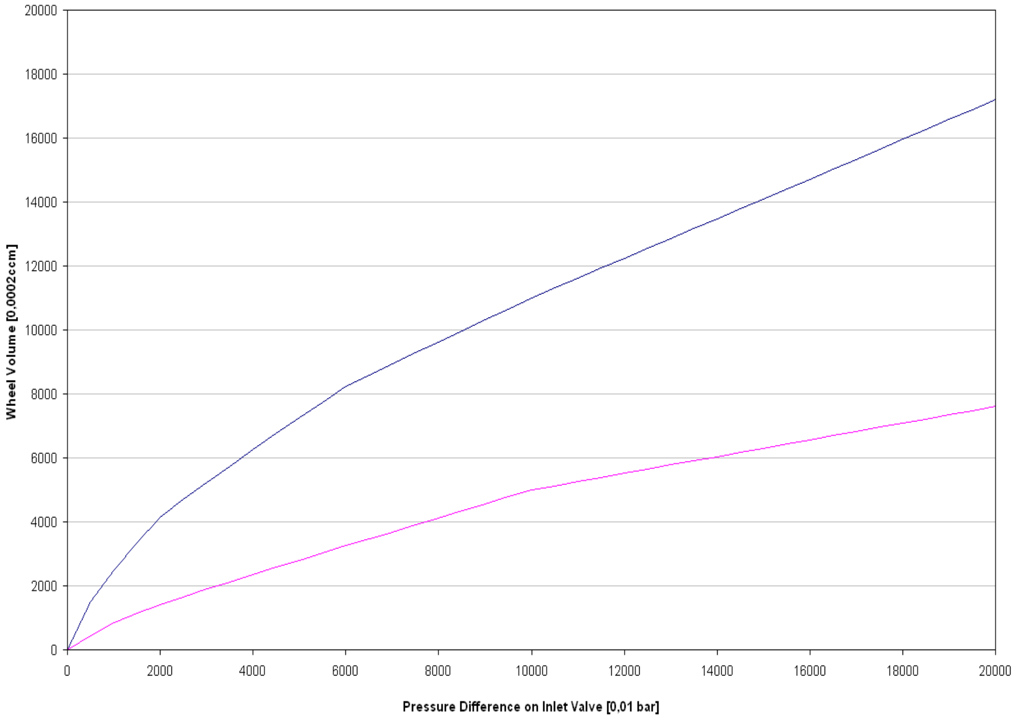


Figure 7: P-V-Curve

The P-V-Curve describes the relationship between both terms to characterize caliper and air gap between disc and pads. It is normally used in the pressure model.

The deriative of the P-V-Curve $C_{Whl} = \frac{dV}{dP}$ describes the linear coherence between the volume flow through the valve and the resulting pressure gradient in the wheel circuit. Compared to an electrical circuit this is the capacity of the hydraulic wheel circuit. Typically, the derivation of the P-V-Curve looks as shown in the figure below.

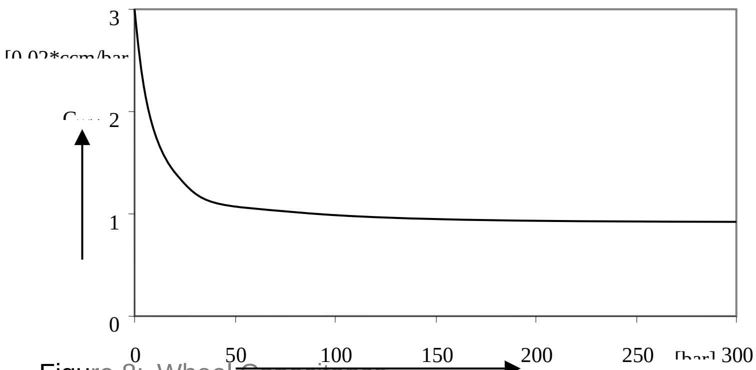


Figure 8: Wheel Capacitance

3.5.2.4 Volume Flow Characteristics

As mentioned earlier, the volume flow stabilises the valve. Each operational point, which is the pressure gradient, depends on the current and pressure difference exerted on the valve. The pressure gradient itself is linked to the volume flow by the P-V-Characteristic.

Therefore a matrix has been determined to characterise a whole operational area of the valve. It comprises a field of characteristics. Each line stands for one constant volume flow.

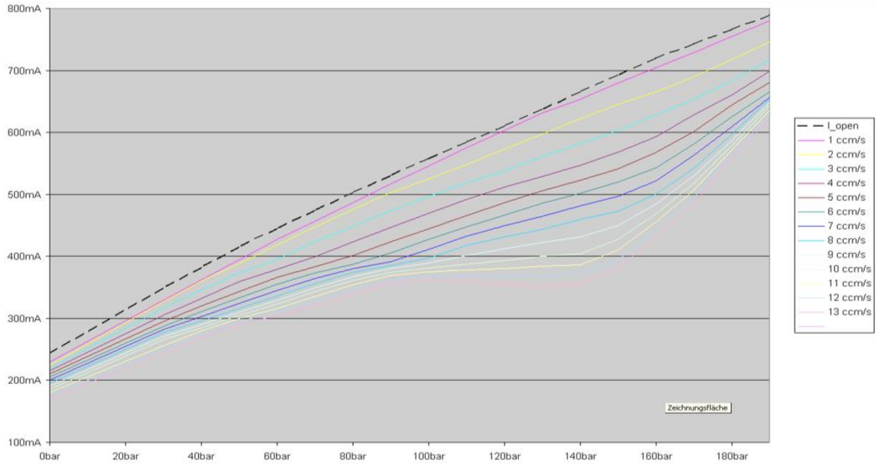


Figure 9: Volume Flow Characteristic (Front Axle)

Now, as the opening characteristic can vary, the above measured characteristic is stored as the ratio of each characteristic to the opening current of the measured valve. The matrix coded looks as follows:

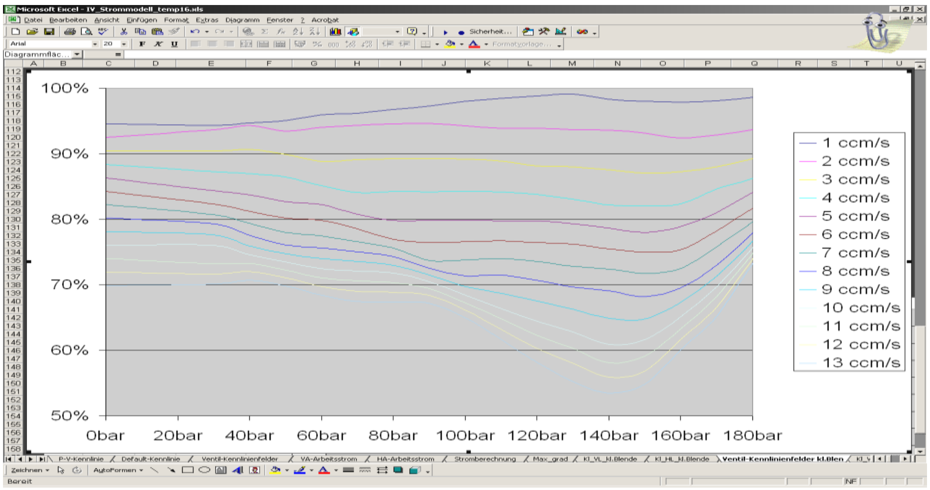


Figure 10: Relative Current

During valve control, the desired gradient is used in combination with the capacity (3.5.2.3) to calculate a desired volume flow. With this a relative current is looked up in the characteristics field shown above. This one is multiplied with the opening current.

3.5.2.5 Control Structure

The opening current is assembled from different parts. As seen above, the first part is the opening current derived from the characteristic in the EEPROM. To set the desired pressure at the desired gradient the relative current i_{grad} is used. This factor is calculated as described in the last chapter. Finally, to correct the current during operation, the adaptive part is determined from the actual control error and the actual gradient. In total the assembled current can be depicted as:

$$I_{IValve}(\ldots) = \underbrace{(I_{open}(\Delta p)_{table})}_{\text{opening characteristic}} \cdot \underbrace{i_{grad}(grad_{cmd}, C_{Wheel}, \Delta p)_{table}}_{\text{gradient characteristic}} - \underbrace{I_{learn}(p_{err})}_{\text{learned part}}$$

The structure is described with the following figure:

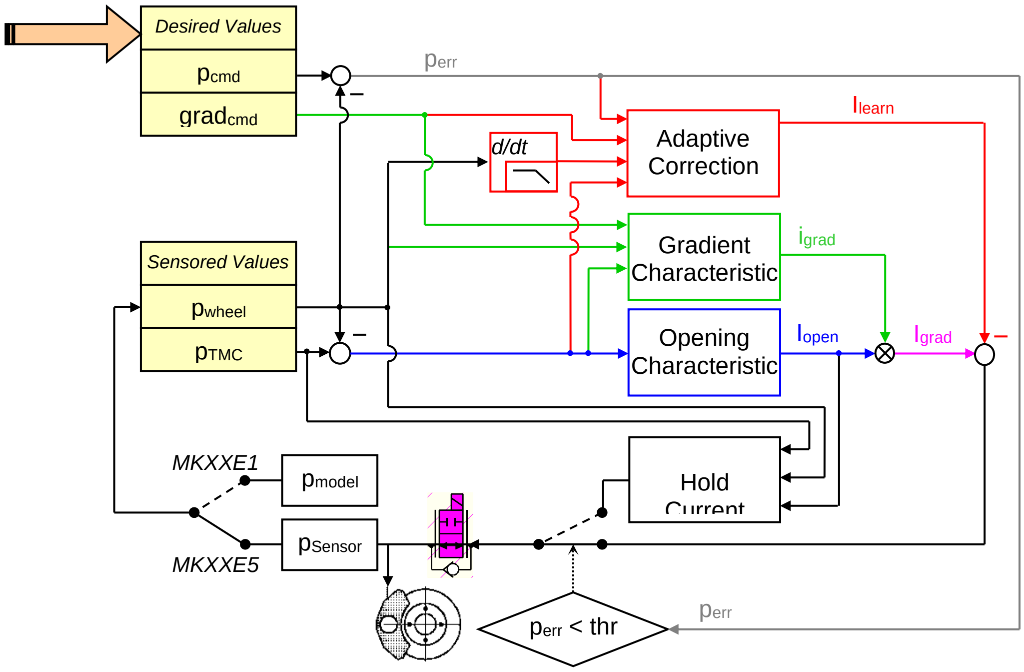


Figure 11: Pressure Increase Control Structure

The diamond in the lower part reflects the valve time calculation and state switch. Thus, it constitues the direct connection to the wheel pressure controller state machine depicted in figure 8 at the beginning of this chapter.

The remaining parts of the control structure shown above all comprise the calculation of the valves' coil current for wheel individual pressure increase regarding the pressure gradient. Notice, that the function block "*Adaptive Correction*" as well as the block "*Hold Current Calculation*" contains different logics, depending on the number of used wheel pressure sensors, respectively the types of coils used in the hardware.

#if (MKxxA)

3.5.2.6 Characteristics

3.5.2.6.1.1 Opening Current Characterisitcs (OCC)

The opening current (I_{open}) of an analogue inlet valve depends on the pressure difference between the system pressure and the wheel. The figure below shows a typical opening current characteristic of an analog inlet valve. The valve characteristic can be different for all 4 wheels.

If the MCI valve is open, the pressure difference on the analogue inlet valve is the difference of TMC pressure and wheel pressure. If the MCI valve is closed, the maximum of the TMC pressure, MCI relief pressure and the two wheel pressures of this circuit is the system pressure of this circuit.

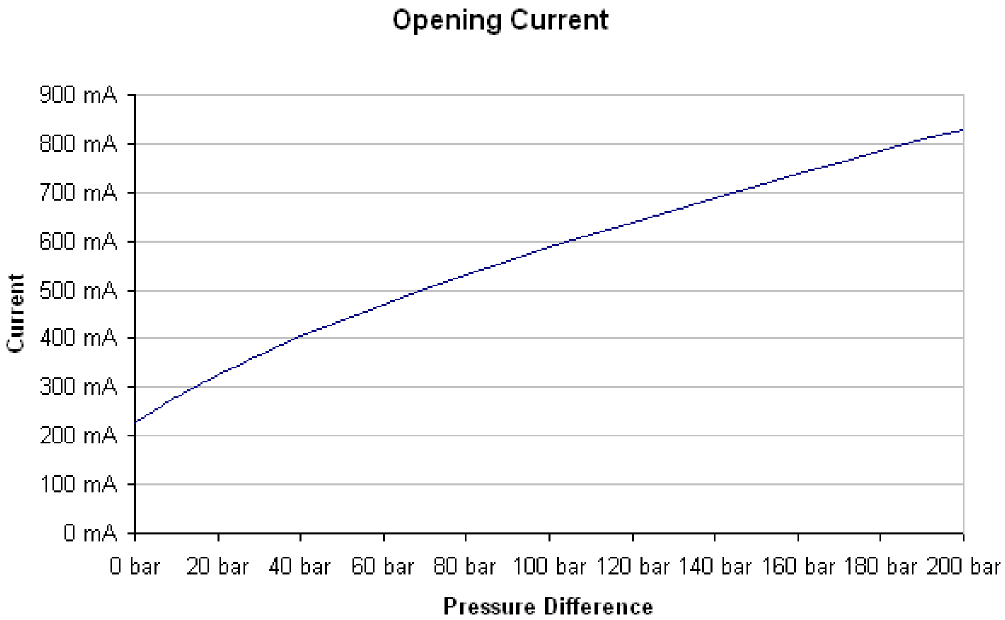


Figure 12: Example of MkxxA ADNO-Characteristic

3.5.2.6.1.2 Pressure-Volume-Characteristic and Capacity

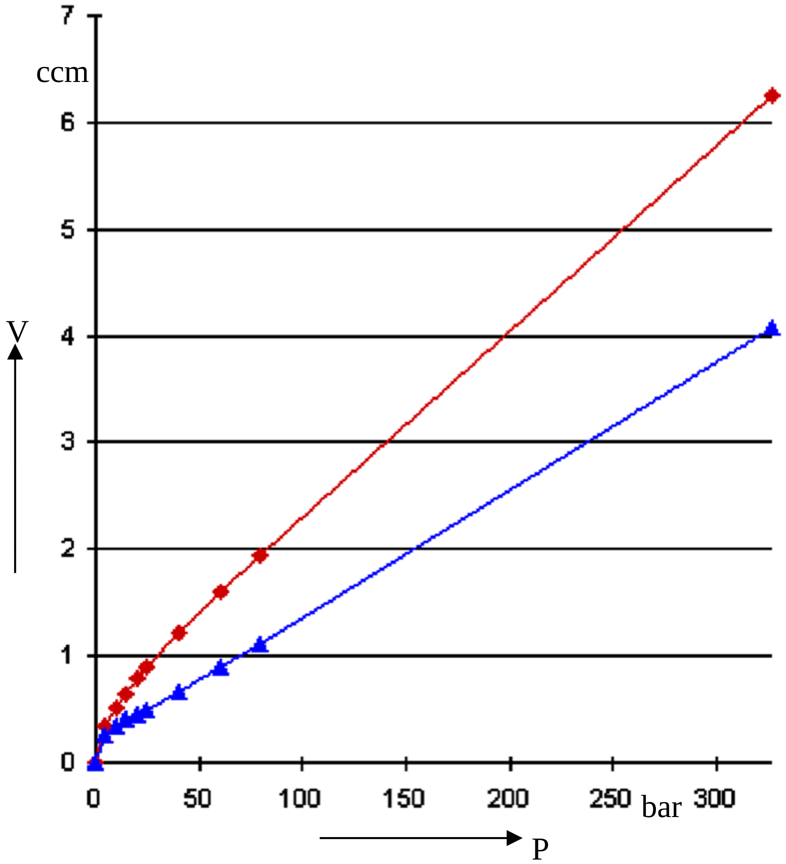


Figure 13: P-V-Curve

The P-V-Curve describes the relationship between pressure and volume to characterize the calliper and brake pads. It is normally used in the pressure model.

The deriative of the P-V-Curve $C_{Whl} = \frac{dV}{dP}$ describes the linear coherence between the volume flow through the valve and the resulting pressure gradient in the wheel circuit: $\dot{P} = \frac{dP}{dt} = \frac{dV}{dt} \div \frac{dV}{dP} = \frac{Q}{C_{Whl}}$.

Typically, the derivation of the P-V-Curve looks as shown in the figure below.

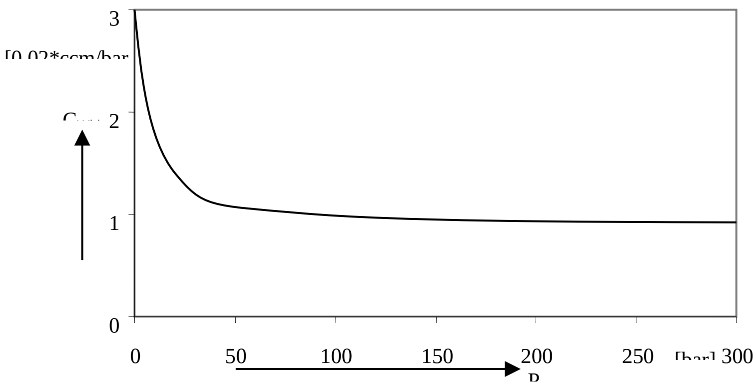


Figure 14: Wheel Capacitance

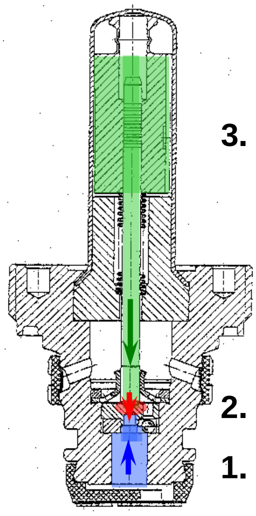
3.5.2.6.1.3 Valve Tappet Stabilization

The tappet of the valve is stabilized by 3 factors:

? Hydraulic Force: is established by the pressure difference on the valve.

? Magnetic Force: is evoked by the valve coil current.

? Flow Force: results out of the volume flow through the partially opened valve.



If all 3 forces are in equilibrium, the valve has a stable operating point. The operating point is set with the correct working current of the valve. This current value depends on the requested pressure gradient, the actual wheel pressure (model) and the pressure difference of the valve.

3.5.2.6.1.4 Opening Current Calculation

The opening current for each valve can be different. Therefore, a special algorithm is used, which is described in this chapter.

3.5.2.6.1.4.1 I0-Adjustment

The system provides the possibility to determine the opening current at only one point: pressure difference ΔP=0bar. This is called I_0-calibration. In addition, the valves are adjusted at the pressure ΔP=125bar. This means, that the valves have the same opening current I_{Adjust} at this point. To calculate the opening current for each valve individually, a default characteristic is stretched by using its I_0, which is stored in the EEPROM. This chapter describes the algorithm for calculating the opening current at every pressure difference, using only I_0 a default opening characteristic.

Data provided:

I_0 :opening current at ΔP=0bar

I_{Adjust} :opening current at ΔP=125bar (identical for all valves due to adjustment process)

$I_{default}(\Delta P_{default})$:default opening current characteristic table (=defchar), using equidistant step width $s_{default}$ between base points

$\Delta P_{0,default} = \Delta P(I_{0,default}) \overset{!}{=} 0bar$:pressure difference at ordinate intercept of defchar

$\Delta P_{\min,default} = \Delta P(I_{\min,default}) = \Delta P\left(n \overset{!}{=} 1\right)$:min pressure difference in defchar (usu. negative)

$\Delta P_{Adjust} = \Delta P(I_{Adjust}) \overset{!}{=} 125bar$:pressure difference of valve adjustment point

$s_{default} = \Delta P_{default}(n+1) - \Delta P_{default}(n) \overset{!}{=} 5bar$:step width of pressure difference values in defchar

Dependent variables:

$\Delta P' = \Delta P_{default}\left(I_{default} = I_{0,Valve}\right)$:pressure difference in defchar, that corresponds to I_0 of the considered valve

$$\boxed{s = \frac{\left(\Delta P_{Adjust} - \Delta P_{0,default}\right)}{\left(\Delta P_{Adjust} - \Delta P'\right)} \cdot s_{default}}$$

:changed step width corresponding to I_0

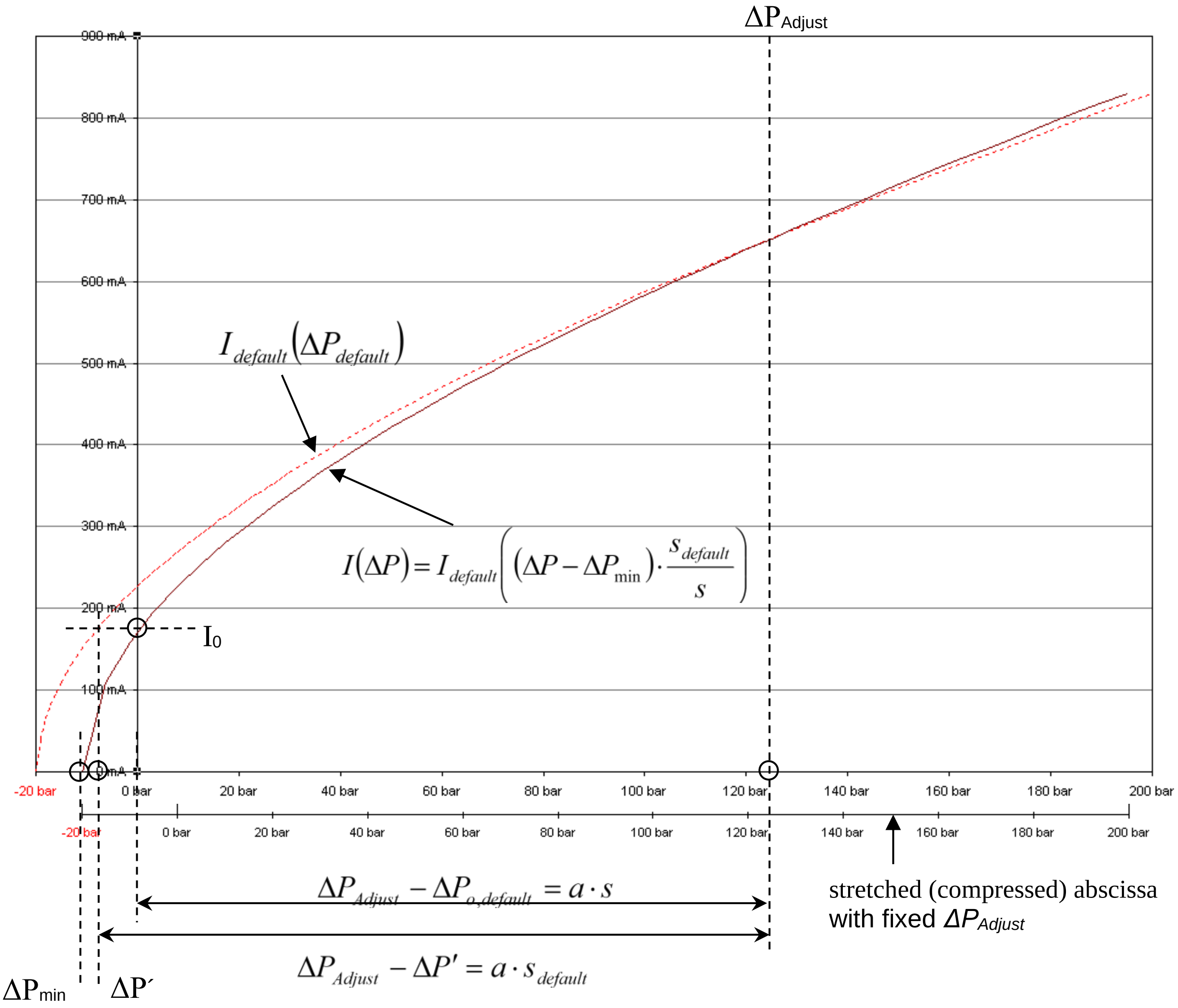
$$\boxed{\Delta P_{\min} = \Delta P_{Adjust} - \left(\Delta P_{Adjust} - \Delta P_{\min,default}\right) \cdot \frac{s_{default}}{s}}$$

:changed min pressure difference corresponding to I_0

$$\boxed{I(\Delta P) = I_{default}\left(\left(\Delta P - \Delta P_{\min}\right) \cdot \frac{s_{default}}{s}\right)}$$

:calculation of opening current

Usage/Example:



3.5.2.6.1.4.2 I125-Adjustment

Furthermore, it might be necessary to adjust the characteristic also at $I_{125} = I_{Open}\left(\Delta P = 125\text{bar}\right)$. Therefore, a simple algorithm is used. An offset to the OCC resulting from chapter 2.4.1 is added to correct the whole caracteristic by keeping I_0 constant:

$$I_{corr}\left(\Delta P\right) = I\left(\Delta P\right) + \left(I_{Adjust,corr} - I_{Adjust,default}\right)\cdot\frac{\Delta P}{P_{Adjust}}$$

3.5.2.6.1.4.3 Combined Adjustment

Finally the calculation of the opening current can be linearly combined of both parts:

$$I\left(\Delta P\right) = I_{default}\left(\overbrace{\left(\Delta P - \Delta P_{min}\right)\cdot\frac{S_{default}}{\underbrace{S}_{=f(I_0)}}}^{I_0\text{-Adjustment}} + \overbrace{\left(\underbrace{I_{Adjust,corr}}_{I_{125};ECU_{cal}} - I_{Adjust,default}\right)}^{I_{125}\text{-Adjustment}}\cdot\frac{\Delta P}{P_{Adjust}}\right)$$

3.5.2.6.1.5 Working Current Characteristics (WCC)

The volume flow stabilises the valve. Each operational point, which is the pressure gradient, depends on the current and pressure difference exerted on the valve. The pressure gradient itself is linked to the volume flow by the capacity.

Therefore a matrix has been determined to characterise a whole operational area of the valve. It comprises a field of characteristics. Each line stands for one constant volume flow.

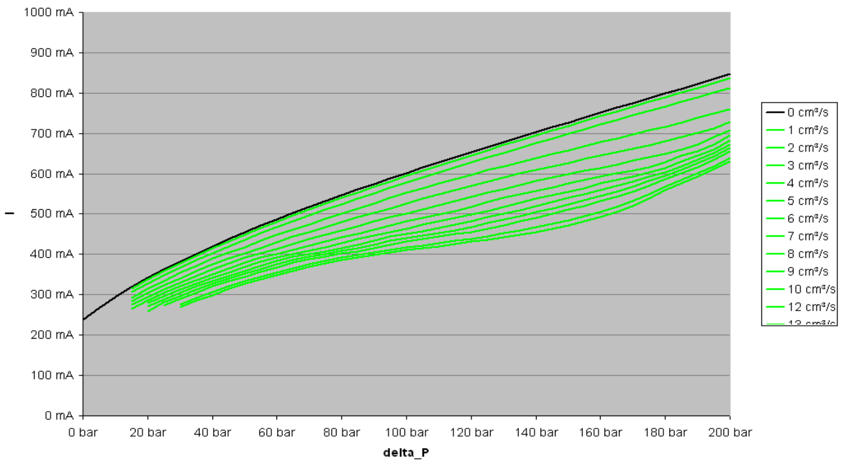


Figure 15: Volume Flow Characteristic (Front Axle)

Now, as the opening characteristic can vary, the above measured characteristic is stored as the ratio of each characteristic to the opening current of the measured valve. The matrix looks as follows:

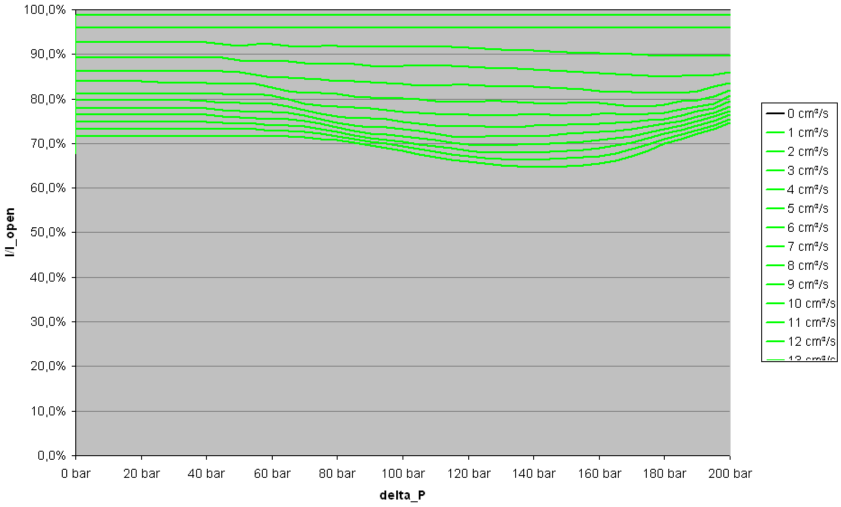


Figure 16: Relative Current

During valve control, the desired gradient is used in combination with the capacity to calculate a desired volume flow. With this a relative current is looked up in the characteristics field shown above. The relative working current characteristics (WCCs) are defined for nominal valves.

3.5.2.6.1.6 Working Current Modification Characteristic (CMC)

The relative working current $i_{work} = {}^{I_{work}(\Delta P,Q)}\!/\!_{I_{open}(\Delta P)}$ is interpolated from the WCC as described in the previous chapter. But as WCCs for non-nominal valves differ from the WCC of a nominal valve, the relative working current has to be modified. The opening current at ΔP=0bar (calibration value) is used as controlling information for the modification.

The relation between one operational point of $WCC_{non\text{-}nominal}$ and $WCC_{nominal}$ can be expressed as the following ratio: $k_{mod}(Q,\Delta P) = \frac{(1-WCC_{non-nominal}(Q,\Delta P))}{(1-WCC_{nominal}(Q,\Delta P))}$. It shows, that this ratio is similar for identical ΔP and different Q. The ratio can be averaged over Q. This leads to one current modification characteristic (CMC) per non-nominal valve: $CMC(\Delta P) = \sum_Q \frac{(1-WCC_{non-nominal}(\Delta P,Q))}{(1-WCC_{nominal}(\Delta P,Q))}$. It shows, that the reciprocal of the CMC derived from nominal and min valve can be used for CMC of max a valve. Therefore, one CMC is stored: $\boxed{CMC(\Delta P) = \sum_Q \frac{(1-WCC_{\min}(\Delta P,Q))}{(1-WCC_{nominal}(\Delta P,Q))}}$

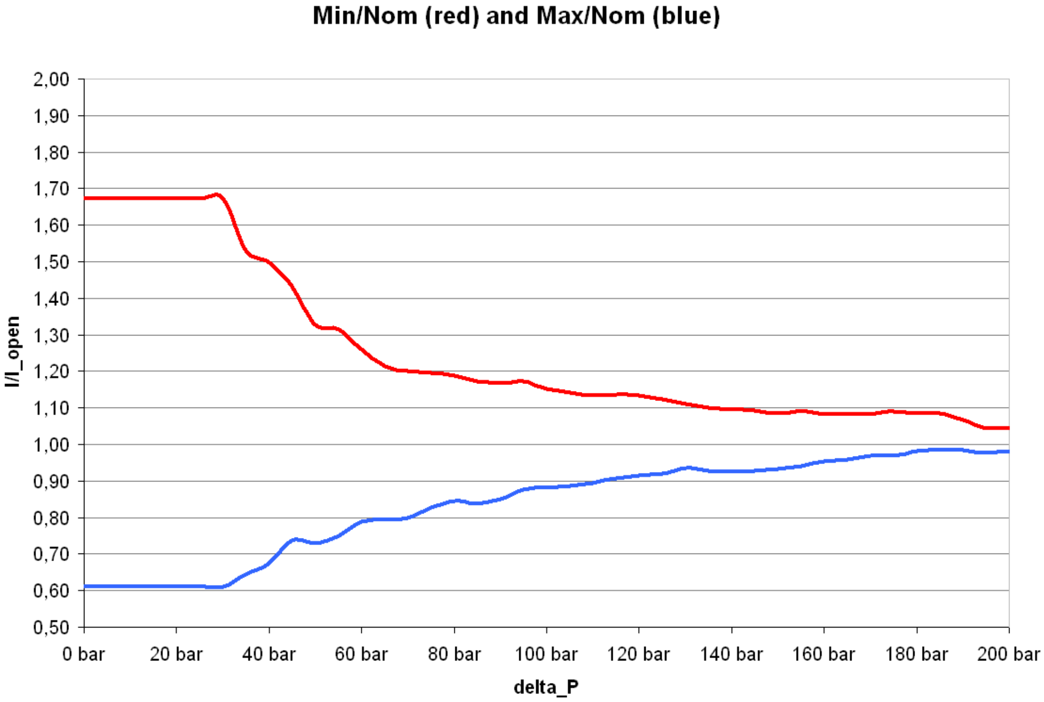


Figure 17: Working Current Modification Characteristics

The modification factor is interpolated between nominal, minimum and maximum valves, depending on the opening current I_0 of the valve. The value is not extrapolated.

It follows:

$$\boxed{\begin{aligned} I_0 \le I_{0,nom} &: k(\Delta P) = CMC(\Delta P)\cdot MAX\left(\frac{I_0 - I_{0,nom}}{I_{0,\min} - I_{0,nom}}, 1\right) \\ I_0 > I_{0,nom} &: k(\Delta P) = \frac{1}{CMC(\Delta P)}\cdot MAX\left(\frac{I_0 - I_{0,nom}}{I_{0,\max} - I_{0,nom}}, 1\right) \end{aligned}}$$

Finally, the relative current is: $\boxed{i = 1 - [1 - i_{work}(\Delta P,Q)]\cdot k(\Delta P)}$

3.5.2.7 Control Structure

The opening current is assembled from different parts. As seen above, the first part is the opening current derived from the characteristic in the EEPROM. To set the desired pressure at the desired gradient the relative current i_{grad} is used. This factor is calculated as described in the last chapter. Finally, to correct the current during operation, the adaptive part is determined from the actual control error and the actual gradient. In total the assembled current can be depicted as:

$$I_{IValve}(\ldots) = \underbrace{I_{open}}_{\text{OCC}} \cdot \left(1 - (1 - \underbrace{i_{work}}_{\text{OCC}}) \cdot \underbrace{k_{CMC}}_{\text{CMC}}\right) - \underbrace{I_{learn}}_{\text{learned part}}$$

The structure is described with the following figure:

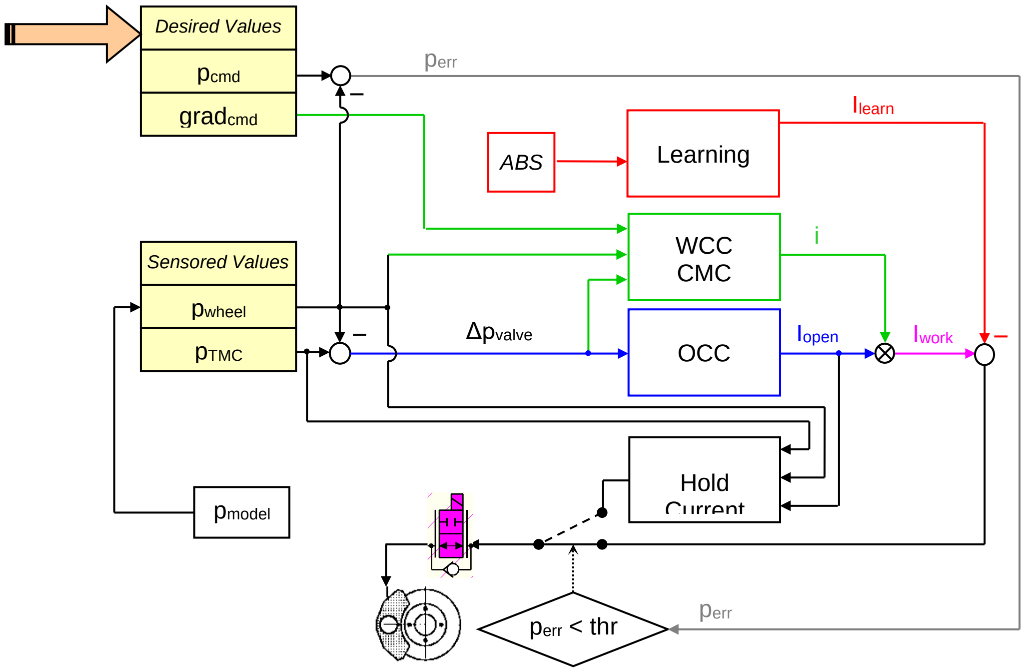


Figure 18: Pressure Increase Control Structure

3.5.2.8 Squeak Avoidance

As the inlet valves are stabilised by the volume flow, under some conditions they start vibrating. This means, a high volume flow around an analog controlled valve can cause mechanical oscillations. The result is a noise often described as "squeaking". To avoid this noise the allowed volume flow can be parameterised and thus limited. During control the pressure gradient for each wheel resulting from the limit is calculated. Any pressure gradient higher than that can cause squeaking noises. The pressure gradient is handed over to higher control functions. These control functions can decide which gradient to request from the inlet valve controller.

Further, there exist PLACC and PDEC_PINC, which are learning algorithms based on independent information from ABS control to improve valve control preciseness during a control. For details, please refer to the according documentation.

```
#endif /*(MKxxA)*/
```

3.5.2.9 Adaptive Correction

As mentioned earlier, the "*Adaptive Correction*" has different logics for systems with 5 pressure sensors and single-sensor systems.

```
#if (MK60E5)
```

3.5.2.9.1.1 Learning Algorithm in 5-Sensor Systems

In addition to the open loop controlled valve current, which is looked up from tables in the non-volatile memory and corrected depending on the desired pressure gradient, the actual wheel pressure and the pressure difference over the valve, an integral current part (I-part) is learned during each control. This current will later be subtracted from formerly calculated value. As the valve is normally open, a positive current will close the valve. Henceforth, a positive I-part will decrease the current in the valve's coil and thus increase in the degree of opening and vice versa.

A positive I-Part (open a valve) is learned by the control error during pressure increase. Reducing the I-Part which means closing a valve is generated by virtue of a detected too big pressure gradient. Both methods are differently priorised and therefore mutually excluded. Furthermore, the learning behaviour depends on the wheel pressure controller's previous and actual control states. Learning cycles are seperated by requested pulses. The following table shows the different (re-)actions:

<table>
<tr><th>Actual
Last</th><th>Calm Down</th><th>Hold</th><th>Increase</th><th>Decrease</th><th>Passive</th></tr>
<tr><td>Increase</td><td colspan="2" rowspan="5">Learning either on
① priority pressure control error
or on
② priority gradient error</td><td></td><td colspan="2" rowspan="5">Reset markers and values for learned states per pulse</td></tr>
<tr><td>Calm Down</td><td rowspan="3">(both: first reset then learn)</td></tr>
<tr><td>Hold</td></tr>
<tr><td>Decrease</td></tr>
<tr><td>Passive</td><td></td></tr>
</table>

Table 9: Learning Behaviour in 5 Sensor Systems

① Priority Pressure Control Error: To guarantee that a valve is opened, the control error in pressure directs the I-Part. This means, if the I-Part is increased by the pressure control error, a gradient error will not be regarded.

② Priority Gradient Error: However, in some cases it is desired to gain the correct pressure gradient, disregarding a possible permanent control deviation. This method brings more comfort on cost of control accuracy.

The I-Part treating by the control error is as follows:

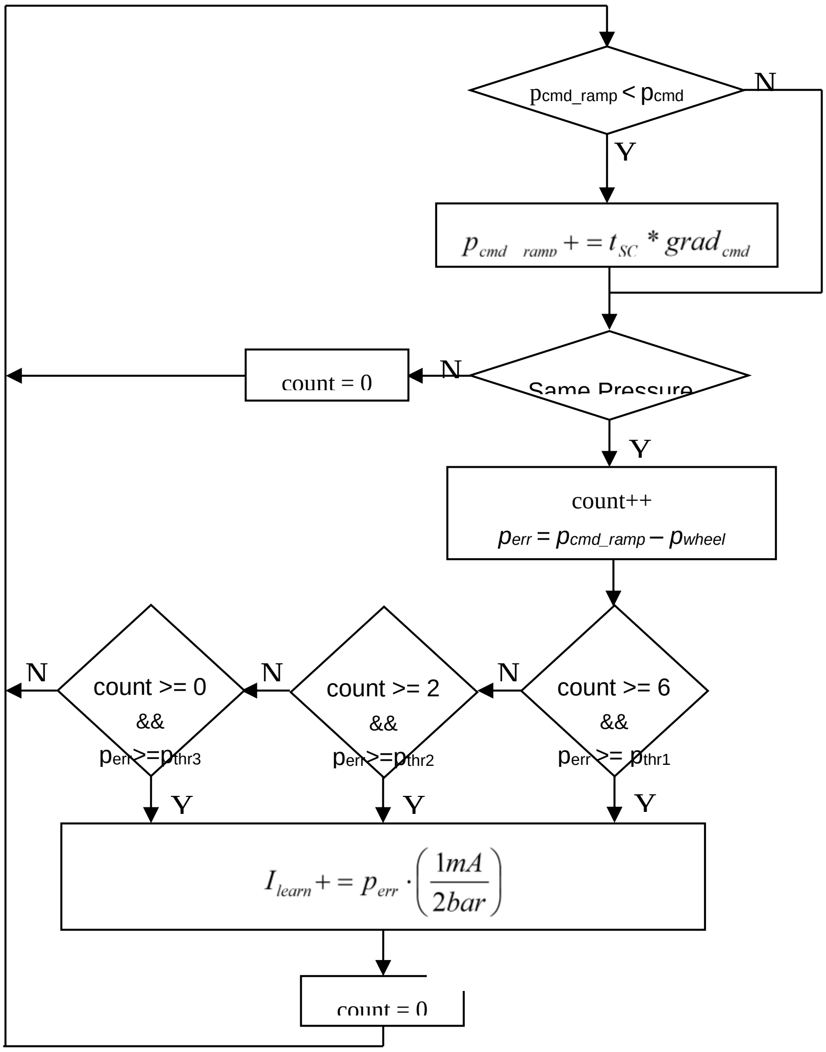


Figure 19: Increase Learning Algorithm on Pressure Deviation

The value p_{cmd_ramp} is the desired pressure ramp, according to the pulse-end pressure command p_{cmd} using the gradient command. It is used to generate the control error. As long as the desired (pulse-end-) pressure and gradient are constant and valid, the same pulse is identified. During one pulse a counter is increased. Only if this counter is greater than a certain value and the control error is bigger than a certain threshold, the I-part is increased. It is, that $thr\_1 < thr\_2 < thr\_3$ for p_{err} whereas the thresholds of the counter rise in opposite direction. The threshold cascading guarantees on the one hand, that big control errors are always considered, and on the other hand that small control errors are regarded only when the counter assures all oscillations to be died away. The increase of the I-Part depends linear on the control error.

The second part of the learning algorithm is used to decrease the I-part to avoid high pressure gradients and thereby make the control more comfortably. It uses the actual gradient of each wheel, which is the derived and filtered pressure signal.

The filter function is: $grad_{wheel}(z) = \frac{4 \cdot (z^{-0} + z^{-5}) + 6 \cdot (z^{-1} + z^{-4}) + 10 \cdot (z^{-2} + z^{-3})}{40 \cdot z^{-0}} \cdot \dot{p}(z)$

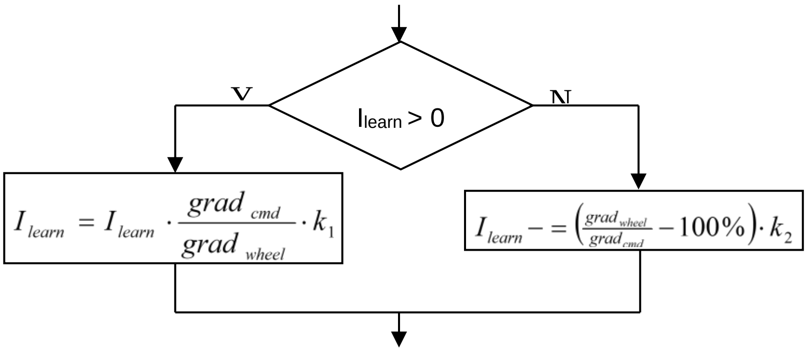


Figure 20: Decrease Learning Algorithm on Filtered Gradient

If an I-part exists, a detected too big pressure gradient is used to reduce that. If the I-part is zero, a negative part is generated by how big is the ratio of detected and desired value.

```
#endif /*(MK60E5)*/
```

```
#if (!MK60E5)
```

3.5.2.9.1.2 Learning Algorithm in non 5 Sensor Systems

As the pressure gradient per wheel cannot be detected by measuring in systems without wheel pressure sensors for every wheel, information concerning the pressure control quality has to be gathered by other means.

The method described below is based upon the information that during subsequent ABS-cycles the blocking pressure stays nearly constant. As during pressure decrease the pressure model is very reliable, the pressure increase cycles can be compared to those.

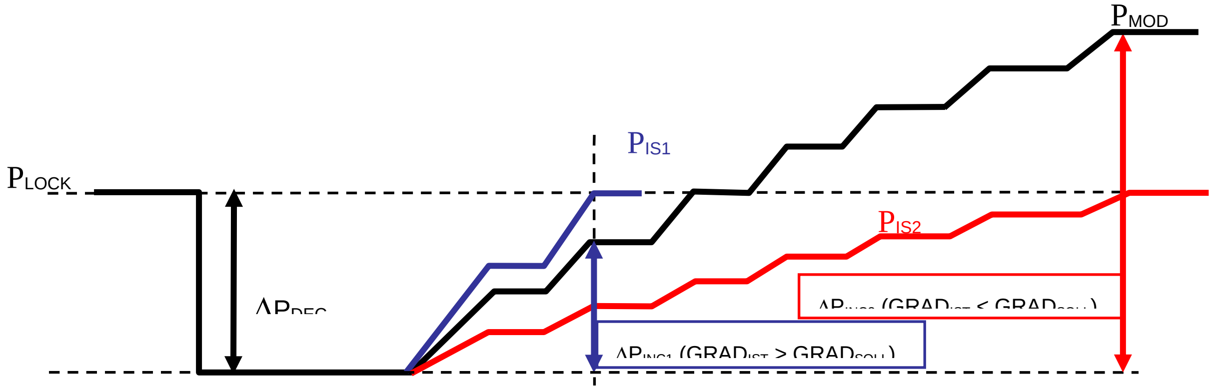


Figure 21: PDEC-PINC-Method

The ratio of P_{inc} to P_{dec} is taken as information to control the I-Part of the pressure controller.

In addition the number of pulses is surveyed. If a wheel comes to block before a number desired pulses is reached or if the desired number of pulses is exceeded, the ratio can be sent instantly by ABS to reduce the rule cycle time.

This information can solely be gathered by the overlying ABS-Control-Algorithm. The ratio is handshaked to the wheel pressure controller. To linearise the behaviour of the I-Part, the ratio is re-calculated. If the ratio s bigger than 100% (real gradient smaller than desired gradient) it is: $\left(\frac{P_{INC}}{P_{DEC}} - 100\%\right) \cdot k = \Delta I$. In this case the I-Part is increased which increases the pressure gradient. If the ratio is smaller than 100% (real gradient bigger than desired gradient) it is recalculated to $\left(100\% - \left(\frac{100\% \cdot 100\%}{\frac{P_{INC}}{P_{DEC}}}\right)\right) \cdot k = \Delta I$. The result is negative and thus decreases the pressure gradient by increasing the valve current. With the factor *k* the current sensibility of this learning algorithm can be adjusted. Test have shown, that 100mA per 100% deviation (after recalculation) serve an advantageous control. For detailled decision and control logics please refer to ABS-documetation. The pressure controller provides only the proportional integration in the valve current calcuation.

```
#endif /*(!MK60E5)*/


#if (MKxxA)
```

3.5.2.9.1.3 PLACC

3.5.2.9.1.3.1 Relation: Pressure over LongAcc

There is a relation between ABS lock pressure and deceleration. This relation can be simplified to a stepwise linear characteristic:

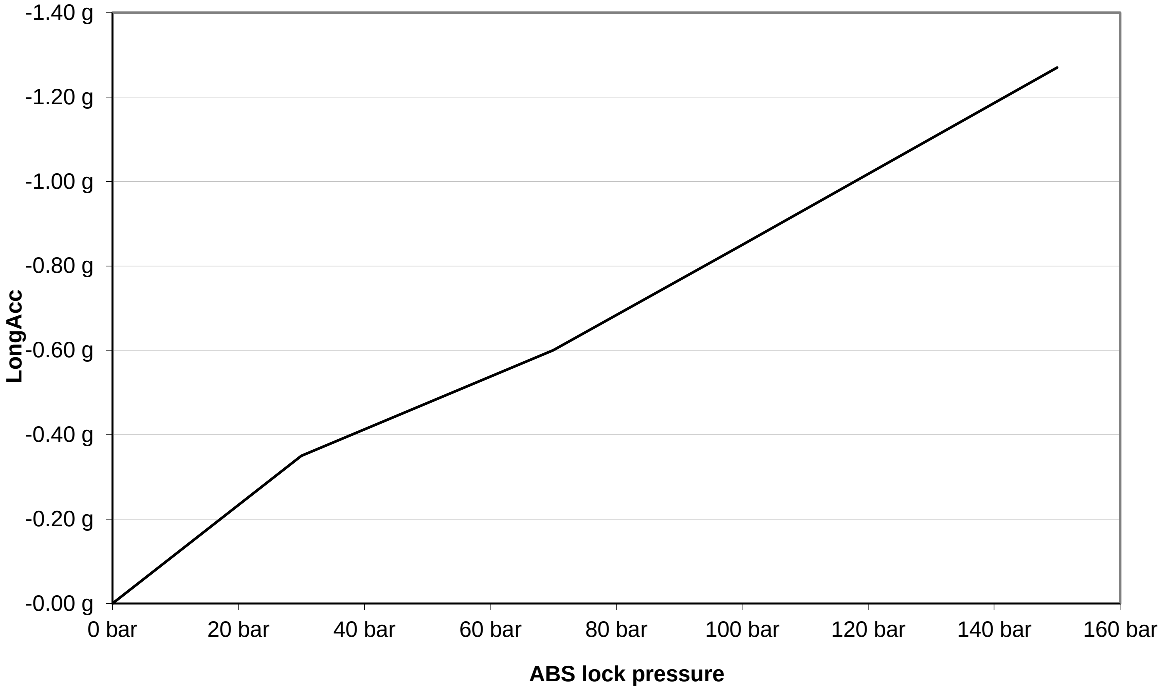


Figure 22: Pressure over LongAcc

The characteristic values depend on the vehicle, tires and road setup.

3.5.2.9.1.3.2 PLACC – Lock Pressure Comparison

The pressure model calculates a wheel pressure according to the open loop controlled inlet valves. Tolerances lead to deviations of the real wheel pressure from the pressure model. The tolerances can be extinguished by adapting the valve current to the individual valve behavior. Therefore, ABS triggers the PLACC algorithm to compare model wheel pressure when the wheel slips (ABS lock pressure) with the pressure that can be derived from the total vehicle deceleration. The deceleration can be derived from either a longitudinal acceleration sensor or the derivative of the vehicle reference velocity. If both pressure values are different while the P-LAcc-characteristic is correct, the valve control must have been imprecise. The relation of both pressures can be taken in consideration for the calculation of an adaptive, integral current offset, that influences the valves behavior.

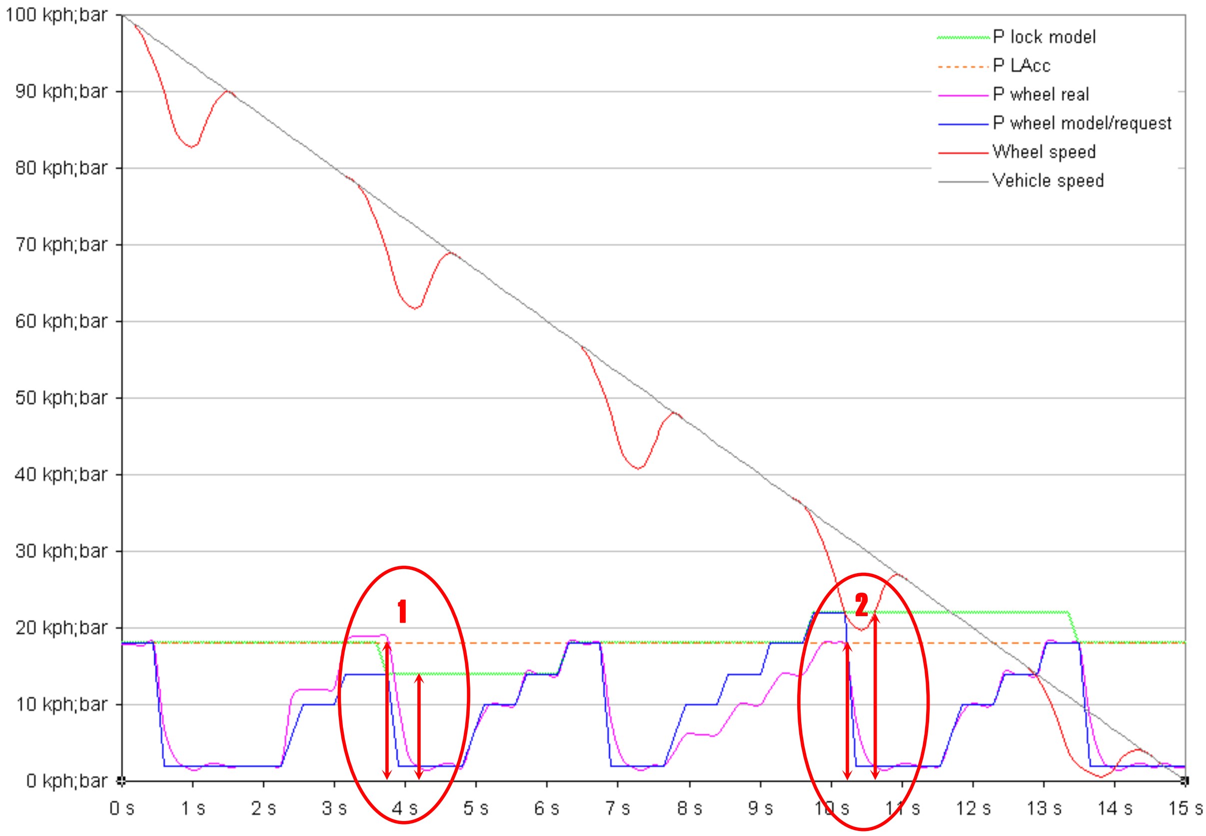


Figure 23: Pressure Situation

Situation 1: $P_{Lock} < P_{LAcc} \Rightarrow$ real pressure increase gradients have been too high $\Rightarrow$ valve current has to be increased.

Situation 2: $P_{Lock} > P_{LAcc} \Rightarrow$ real pressure increase gradients have been too low $\Rightarrow$ valve current has to be decreased.

3.5.2.9.1.3.3 Current offset calculation

If one of the situations shown in the previous chapter occurs, the current offset for the valve is calculated as follows:

$$\left.\begin{array}{l} P_{Lock} > P_{LAcc} : Q_{err} = 1 - \frac{P_{Lock}}{P_{LAcc}} \Rightarrow Q_{err} < 0 \\ P_{Lock} < P_{LAcc} : Q_{err} = \frac{P_{LAcc}}{P_{Lock}} - 1 \Rightarrow Q_{err} > 0 \end{array}\right\} \Delta I_{Valve} = k \cdot Q_{err}$$

PLACC correction calculation only is processed above certain TMC pressure and vehicle deceleration thresholds.

```
#endif /*(MKxxA)*/
```

3.5.3 Interface to control functions

In the interface to control functions the following information is included. The control functions must take account of these restrictions.

Get_min_inc_req_pres(x)
Description: returns the minimum wheel pressure after a pressure increase of the selected wheel channel x (wheel valve control (normally open valve)); if the pressure request is greater than or equal to this value, it is guaranteed that a increase pulse will be given

Get_min_req_inc_pres_gradient(x)
Description: returns the minimum requested pressure gradient for pressure increase for the selected wheel channel x

Get_max_req_analog_inc_pres_gradient(x)
Description: returns the maximum requested pressure gradient (analogue) for pressure increase for the selected wheel channel x

Get_max_req_inc_pres_gradient(x)
Description: returns the maximum requested pressure gradient (digital) for pressure increase for the selected wheel channel x

4 Technical Safety Concept of the Hydraulic Modulator

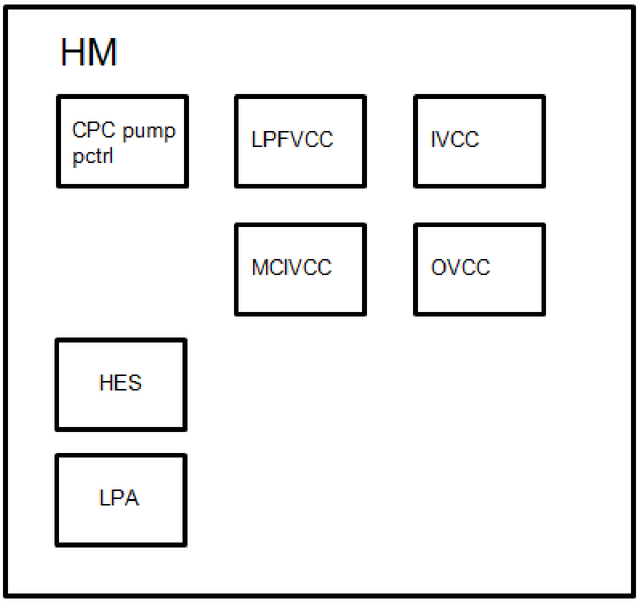
4.1 Introduction

4.1.1 Components

The Hydraulic Modulator basically consists of the following components

- Circuit Pressure Control, responsible for pressure increase, hold and decrease in the single brake circuits using MCI Valve Control Chain, LPF Valve Control Chain and Hydraulic Energy Supply Chain.
- Wheel Pressure Control Chain, responsible for wheel individual pressure increase, hold, and decrease using Inlet Valve Control Chain, Outlet Valve Control Chain, LPA Control Chain and Hydraulic Energy Supply Chain.

The following figure illustrates the mentioned components:



HM: Hydraulic Modulator
CPC pump pctrl: CPC pump pressure control
LPFVCC: LPF valve control chain
MCIVCC: MCI valve control chain
IVCC: Inlet valve control chain
OVCC: Outlet valve control chain
HES: Hydraulic energy supply control chain
LPA: Low pressure accumulator control chain

The Circuit Pressure Control Chain consists of a module defining the requested pump speed (pump pressure control), the MCI Valve Control Chain and the LPF Valve Control Chain.

The rule of the MCI Valve Control Chain is to define the current level necessary for pressure increase, hold and decrease.

The rule of the LPF Valve Control Chain is to define whether the pump shall be supplied with the brake fluid from TMC or from LPA or not to be supplied at all.

4.1.2 Use cases

In this chapter use cases are described illustrating the typical operation of the Hydraulic Modulator.

4.1.2.1 Use case “Active pressure increase, hold and decrease” in a system w/o wheel pressure sensors

4.1.2.1.1 Functional description

Assumption: The brake pressure shall be increased from 0 to 15bars within 1.5s in both brake circuits from any function. After the increase phase the pressure shall be hold for 1s. After that phase the pressure shall be decreased within 1.5s.

If the arbitration decides that the pressure request shall be processed the single control chains the requests are processed to the single control chains.

Pressure increase phase:

The MCI Valve Control Chain decides about the electrical current that is necessary to apply the requested pressure level in the current loop. If the difference between the requested pressure and the modeled pressure exceeds a certain electrical current level corresponding to the pressure level is applied.

The LPF Valve Control Chain decides about the pump supply. If the volume in the LPA is 0 and the difference between the requested pressure and the modeled pressure exceeds a certain pressure level the LPF valves are activated. The electrical current level for secure activation is defined.

The pump pressure control module of the Circuit Pressure Control Chain decides about the requested pump speed. If the difference between the requested pressure and the modeled pressure exceeds a certain pressure level and the MCI Valve Control Chain signals that the necessary current is applied the respective pump speed is determined. The request pump speed is determined taking the following signals into consideration volume need (based on the connected consumers) and the requested pressure dynamic.

The activities of these components are observed by the pressure model that generates the information about the current pressure level. If the requested pressure level is approximately reached an overflow volume flow over the MCI valve is calculated.

The MCI Valve Control Chain takes this overflow volume from into account and adapts the requested current in that manner that despite the fact that the pressure level is reached the applied pressure level does not exceed the requested pressure level.

If the requested pressure level is reached a certain minimum pump control time is over the Circuit Pressure Control Chain switches the pump off.

The MCI Valve Control Chain takes care about the change of the MCI valve overflow and adapts the requested electrical current. If the pump is standstill the MCI Valve Control Chain requests an electrical current necessary for secure pressure hold.

Pressure hold phase:

In pressure hold phase MCI Valve Control Chain requests an electrical current necessary for secure pressure hold.

Generally in pressure hold phase the LPF Valve Control Chain closes the LPF valves.

Generally in pressure hold phase the Circuit Pressure Control Chain request a pump speed of 0.

Pressure decrease phase:

If the difference between the requested pressure and the modeled pressure exceeds a certain pressure threshold the MCI Valve Control Chain requests an electrical current corresponding to the pressure level is applied. Depending on the pressure gradient the electrical current request is done in steps considering special actuator needs.

The LPF Valve Control Chain keeps the LPF valve closed.

The pump pressure control module of the Circuit Pressure Control Chain requests a pump speed of 0.

Note:

For the application of any valve request the main driver has to be switched. Otherwise no valve current control is possible.

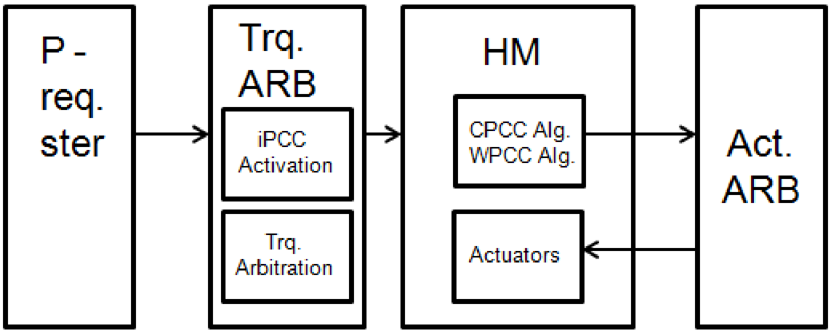
4.1.3 Safety aspects – How to make sure that the software of the Hydraulic Modulator does not trigger a pressure unintended

The control moduls (CPCC, WPCC) are only addressed if they are enabled by the arbitration. The arbitration module operates in separate task and RAM section. The RAM section is specially monitored concerning unauthorized access.

Further the active pressure increase is only performed if the three modules decide that active pressure increase is necessary.

The actuator requests are put via separate interfaces into the special RAM section that is protected as specified above. The data are only passed to the single controller if the arbitration decides that there is a respective request for actuator control.

The following figure illustrates roughly the signal flow.



P- req. ster: pressure requesting components
Trq. ARB: Brake torque arbitration
iPCC Activation: Activation of CPCC and WPCC
Trq. Arbitration: Brake torque arbitration
Alg.: Algorithm
Act. ARB: Actuator request arbitration

Besides the complete EBS software is executed in 2 cores two times. The output is compared by a hardware module that switches off the ECU in case of any deviations.

All valves receive the valve request from MCU via SPI.

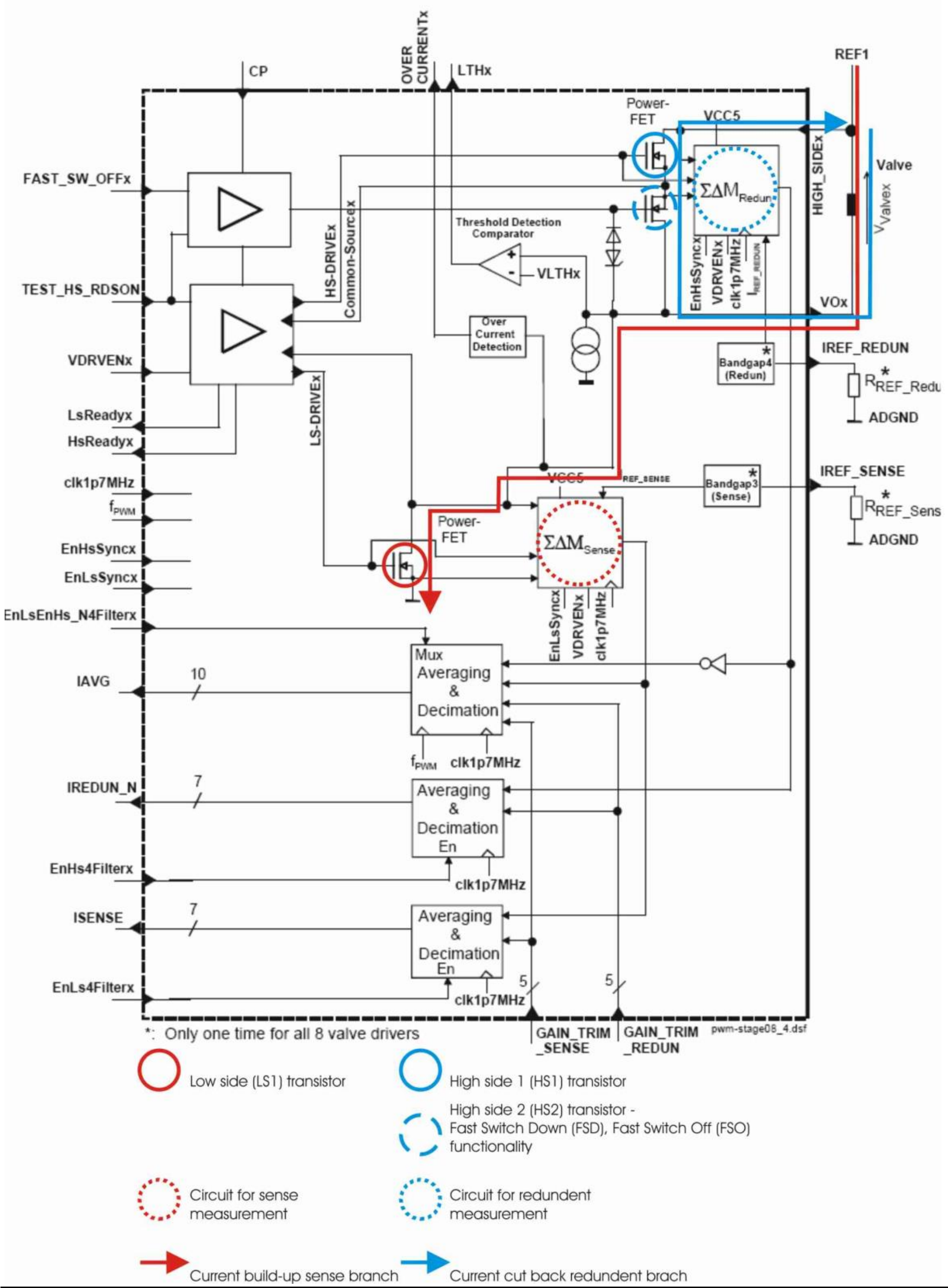
PCU and MCU are synchronized via a WATCHDOG word that has to be correct and arrive in time. Otherwise a WATCHDOG failure is recognized forcing a disable of all valve stages via a separate pin that inhibits valve activation.

4.1.4 Safety aspects – How to make sure that the actuators work as intended – MCI Valve Control Chain/LPF Valve Control Chain/Inlet Valve Control Chain

The following valve control chains are described in the same chapter as the valve stages have the same features.

- MCI Valve Control Chain
- LPF Valve Control Chain
- Inlet Valve Control Chain

The following figure illustrated roughly the physical architecture of the valve stages. The



Common Details can be found here and here.

4.1.4.1 Use case “at least one valve activated” – supervisions at the active valves

This chapter illustrates the supervisions of the activated valves in case that at least one valve is activated.

Example: Pressure increase phase/pressure hold phase/pressure release phase – MCI Valve Control Chain

For the application of any valve request the main driver has to be switched. Otherwise no valve current control is possible. The requested electrical current (I_set) is controlled using a current controller. The current feedback path is realized in hardware (I_avg).

Supervision (I_sens versus I_redundant):

The applied electrical current is measured via ADC (2 channels; I_sens, I_redundant). The differences between the 2 channels are monitored by software. In case of deviations the valve chains are switched off.

See chapter Appendix Valve current monitoring for detailed information.

Rationale: Make sure that the measurement channels work.

Supervision (I_set versus I_avg):

Besides the average applied current (I_avg) is compared by the software with the requested current (I_set). In case that the deviation exceeds a certain threshold all valve stages are switched off.

Rationale: Make sure that the current controller works.

Supervision (I_set versus (I_sens + I_redundant)/2):

Besides a calculated average current ((I_sens + I_redundant)/2) is compared by the software with the requested current. In case that the deviation exceeds a certain threshold all valve stages are switched off.

Rationale: Make sure the hardware of the PCU (I_avg) is correct.

The MCI valve current supervisions monitor the currents 2 times within 10ms. For robustness reasons a failure has to be detected 2 times to trigger a failure reaction.

Note:

The current controller is implemented as PWM. The signal I_redundant is the current in the recirculation path (green path in the figure). This is generally only possible for duty cycle values lower than 100%. Thus the maximum duty cycle is limited in that manner that the signal I_redundant can be provided.

Lth Supervision:

In case that there is any valve current request the voltage level at Vox is checked (Lth). In case of an activated low side driver (LS_DRIVEx) the voltage must be lower than a certain threshold (for instance 2.2V). This is done by a hardware comparator and software evaluation of the respective flag (LTHx).

Rationale: Make sure that the low side driver switches correctly.

4.1.4.2 Use case “at least one valve activated” – supervisions at the passive valves

This chapter the supervisions of the passive valves in case that at least one valve is activated.

Example: Pressure increase phase/pressure hold phase/pressure release phase – LPF Valve Control Chain

In case that the LPF valve is activated the supervisions work as specified in ”Example: Pressure increase phase/pressure hold phase/pressure release phase – MCI Valve Control Chain”.

Lth Supervision:

In case of a deactivated low side driver (LS_DRIVEx) the voltage must be higher than a certain threshold (for instance 2.2V). This is done by a hardware comparator and software evaluation of the respective flag (LTHx).

To check the switching behavior a test pulse (for instance 50us) is given to the low side driver. In case that the flag (LTHx) changes state everything is o.k.. Otherwise a failure is detected as soon as flag does not change 8 times.

In the LPF valve control chain the check of the LTHx flag is checked once each 10ms. Thus the detection of this failure takes at least 80ms.

Rationale: Make sure that the low side driver switches correctly. 80ms are below the vehicle reaction time.

Note:

This procedure is executed for every not activated valve in case that at least one valve is activated.

For MCI valves a failure is detected as soon as 2 events have been detected where the check is executed twice in 10ms.

Rationale: Make sure that the low side driver switches correctly. 20ms must be kept to meet burst pressure requirements (Assuming that the pump runs and all valves are powered due to a PCU failure it takes 20ms to reach critical system pressure levels.).

4.1.4.3 Use case “no valve activated” – supervisions at the passive valves

This chapter illustrates the supervisions in case that all valves are not activated.

Example: No valve request

In case that here is any valve request the main driver is not switched. To monitor the electrical operation of the valves a test pattern is executed (2 subsequent steps, “passive test pulses”):

Step 1: Activation of a leakage current source (LCS)

A leakage source current is activated at REF1. The current is limited to 10mA thus there are no hydraulic effects. The low side driver is off. In case that the voltage at REF1 corresponds approx. to the KL30V voltage everything is o.k.

Rationale: Obviously there is no other connection the GND than by the low side driver and the coil is correctly connected.

Step 2:

The low side drivers (LS_DRIVEx) are switched sequentially for every valve (for instance for 2ms) and the voltage REF1 is monitored. In case that the voltage level does not drop below a certain threshold (for instance 3V) a failure event is generated. The stage is switched off after 8 events where the check is executed once in each 10ms; the MCI valves stages after 2 events where the check is executed once in each 5ms.

Rationale: This procedure detects a not switchable low side driver and the coil is correctly connected.

4.1.4.4 Use case “power on/ignition on” – supervisions executed once

This chapter illustrates the supervisions that are executed once typically close to the power up of the ECU.

At the beginning of the ignition cycle the MCI valve characteristic is calculated reading parameters from EEPROM. The resulting characteristic in RAM is checked. If the characteristic is out of tolerance an error is detected the MCI Valve Control Chain is disabled.

At the beginning of the ignition cycle the inlet valve characteristic is calculated reading parameters from EEPROM. The resulting characteristic in RAM is checked. If the characteristic is out of tolerance an error is detected the Circuit Pressure Control Chain is disabled and the Inlet Valve Control Chain is forced to digital control.

At the beginning of the ignition cycle the ECU calibration data in RAM is checked. If an error is detected the Circuit Pressure Control Chain is disabled and the Inlet Valve Control Chain is forced to digital control.

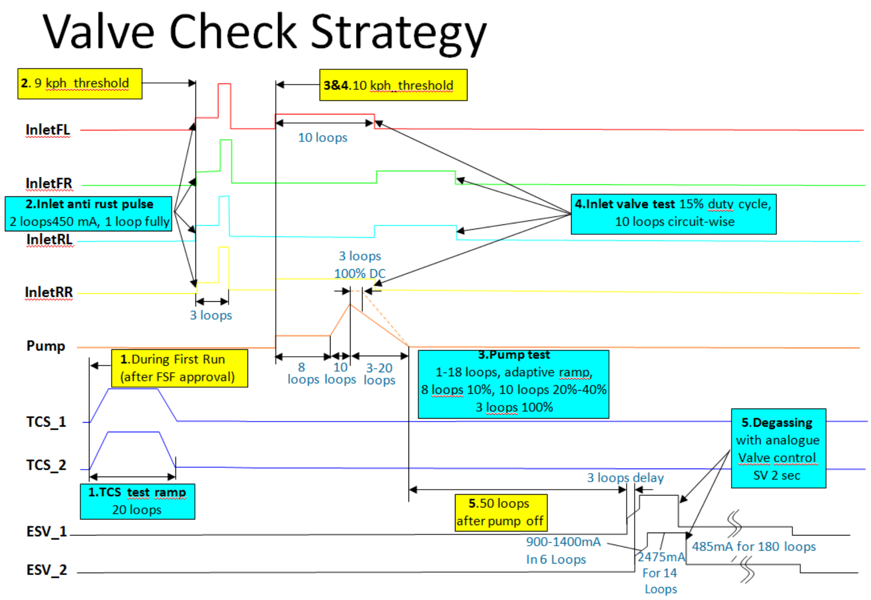
For verification of the general availability of the MCI valve current controller a current pattern is automatically triggered at a time typically close to power up the ECU.

For verification of the general availability of the inlet valve current controller a current pattern is automatically triggered at a time typically close to power up the ECU.

The general availability of the LPF valve current controller is verified by a trigger of a degassing routine after pump test at a time typically close to power up the ECU.

Rationale: Make sure that the current controller works as specified.

The following figure illustrates the valve checks at a time typically close to power up the ECU. The figure contains typical valves.



Hydraulic Modulator: Initial Check

See http://ffm-mks3.er1.ate:7001/si/viewrevision?projectName=d:/mks/archives/projectdocs/AbC/110%5fSoftware/20%5fSWDesign/SALayer/SupportServiceHandler/project.pj&selection=SW%5fDesign%5fSSH%5fSupport%5fService%5fHandler.docx
For further information concerning initial check.

4.1.4.5 Use case “power permanent on/ignition permanent on”

This chapter illustrates the supervisions that are executed permanently in the powered ECU regardless of the valve activation state.

Maximum temperature of the PCB (“thermal shutdown”):

The temperature of the valve stage is monitored permanently. In case that a certain threshold (for instance 200°C) is exceeded the MCI valve control chain is disabled until certain lower threshold not exceeded.

The shutdown is done by hardware. The shutdown affects all valve stages. The software detects the switch off by the Lth supervision and switches off the main driver.

Maximum current (“overcurrent”):

The electrical current driven by the valve stage is monitored permanently. In case that a certain threshold (for instance 4A) is exceeded the valve stage is disabled by hardware. The software detects the switch off by the Lth supervision and switches off the main driver.

Maximum valve stage supply voltage (“overvoltage”):

The voltage at the point REF1 is monitored. In case that the deviation exceeds a certain threshold all valve stages are switched off.

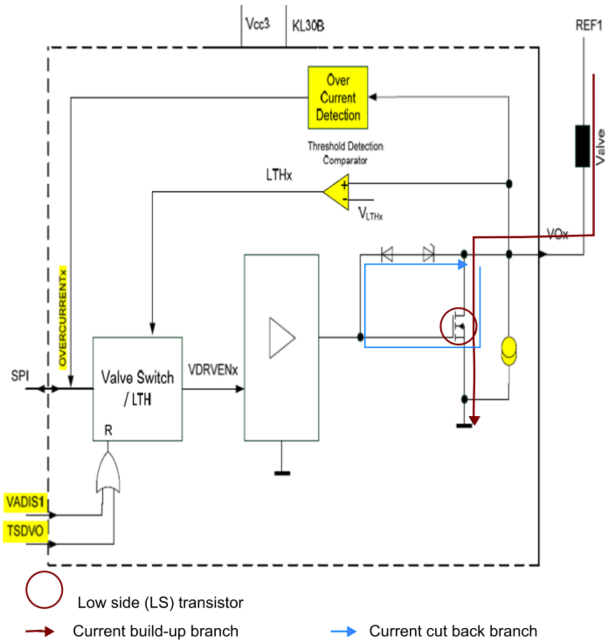
4.1.4.6 Further information

Further information can be found at http://ffm-mks3.er1.ate:7001/si/viewrevision?projectName=d:/mks/archives/projectdocs/IAT%20Hydraulic%20Modulator/90%5fOthers/project.pj&selection=Failsafe%20Ventilstufen%20und%20Temperatursensor.pptx

See SRS 2 Generic MCI Valve Control Chain ID 1734626 for further information.
See SRS 2.0 MK100 WPC ID 439856 for further information.

4.1.5 Safety aspects – How to make sure that the actuators work as intended – Outlet Valve Control Chain

The Outlet Valve Control Chain possesses a digital valve stage. There is no current control.
The following figure illustrated roughly the physical architecture of the valve stages.



The supervision mechanisms are described in the previous chapter. Note that all supervisions related to current control does not apply for the Outlet Valve Control Chain.

See SRS 2.0 MK100 WPC ID 439856 for further information.

4.1.6 Safety aspects – How to make sure that the actuators work as intended – LPF Valve Control Chain - details

See MCI Valve Control Chain concerning architecture and supervisions.

See SRS 2 Generic LPF Valve Control Chain ID 1736961 for further information.

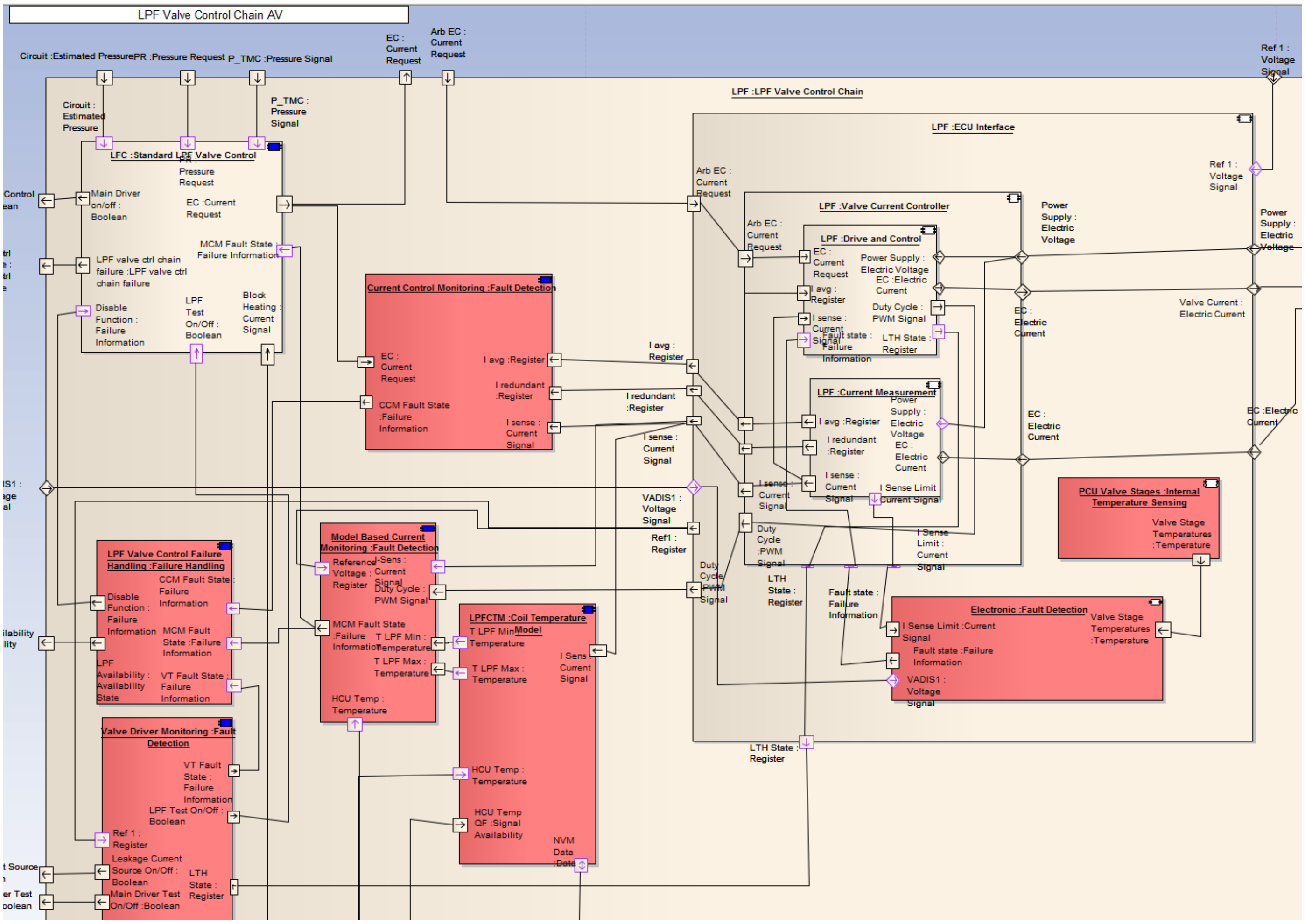


Figure 24: Architecture LPF Valve – Safety Blocks in Red

[Link to Enterprise Architect]

4.1.6.1.1 PCU Valve Stages :Internal Temperature Sensing

Input:

- (Own Temperature)

Output:

- PCU Valve Stages Temperature

4.1.6.1.2 Electronic :Fault Detection

Input:

- PCU Valve Stages Temperature
- I Sense Limit: Current Signal
- VADIS1: Voltage

Output:

- Fault state :Failure Information

4.1.6.1.3 LPF Valve Control Failure Handling :Failure Handling

Input:

- Current Control Monitoring Fault State :Failure Information
- Valve Driver Monitoring Fault State :Fault Detection

Output:

- Disable Function : Failure Information
- LPF Availability :Availability State

4.1.6.1.4 Valve Driver Monitoring :Fault Detection

Input:

- LTH State : Register
- Ref1 : Register

Output:

- Valve Driver Monitoring Fault Sate : Failure Information
- LPF Test On/Off : Boolean
- Leakage Current Source ON/Off : Boolean
- Main Driver Test On/Off :Boolean

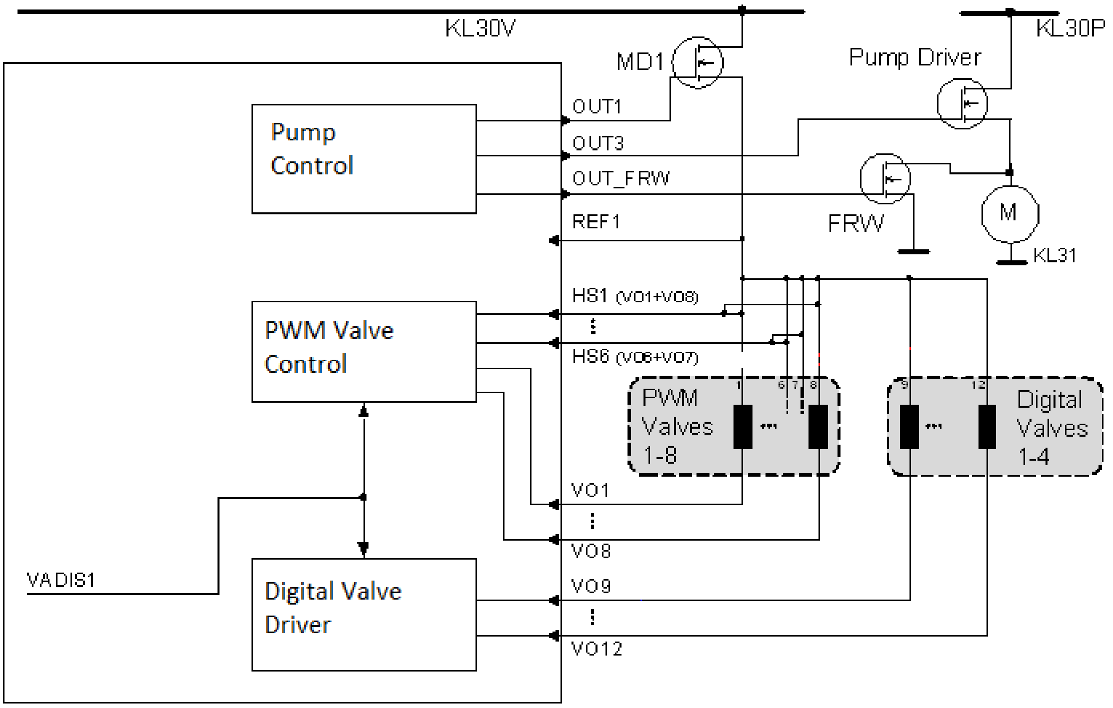
4.1.7 Safety aspects – How to make sure that the actuators work as intended – Hydraulic Energy Supply Chain

The failsafe concept is described in http://ffm-mks3.er1.ate:7001/si/viewrevision?projectName=d:/mks/archives/projectdocs/IAT%20Hydraulic%20Modulator/30%5fPump/20%5fDescriptions/Failsafe/project.pj&selection=Pump%20Driver%20Failsafe.ppt

See SRS 2 Generic Pump Control Chain ID 1737310 for further information.

4.1.8 Safety aspects – How to make sure that the actuators can be switched off in any case

The following figure illustrates roughly the physical connections between the actuators.



Digital as well as analogue valve states can be switched once by the control logic of the single valves as well as by switching off the main driver MD1. The correct operation of the main driver is monitored.

<u>Main driver switching behavior check:</u>

At ignition of the voltage at REF1 must not exceed 6V+/-0.5V in case that the main driver is switched off. Otherwise the valves will be disabled.

If the main driver is switched the voltage at REF1 shall be 6V +/-0.5V. Otherwise the valves will be disabled.

<u>Leakage Current Detection (KL30 --> REF):</u>

A leakage current is detected, when the main driver and the leakage current source of the main driver are not activated, but the voltage level at the REF node exceeds the threshold.

Leakage Current Detection (REF --> GND):

Leakage current tests are done during the drivers OFF state. A current source between main driver drain and main driver source is activated. A leakage is detected if the voltage drop across the active current source exceeds a certain threshold.

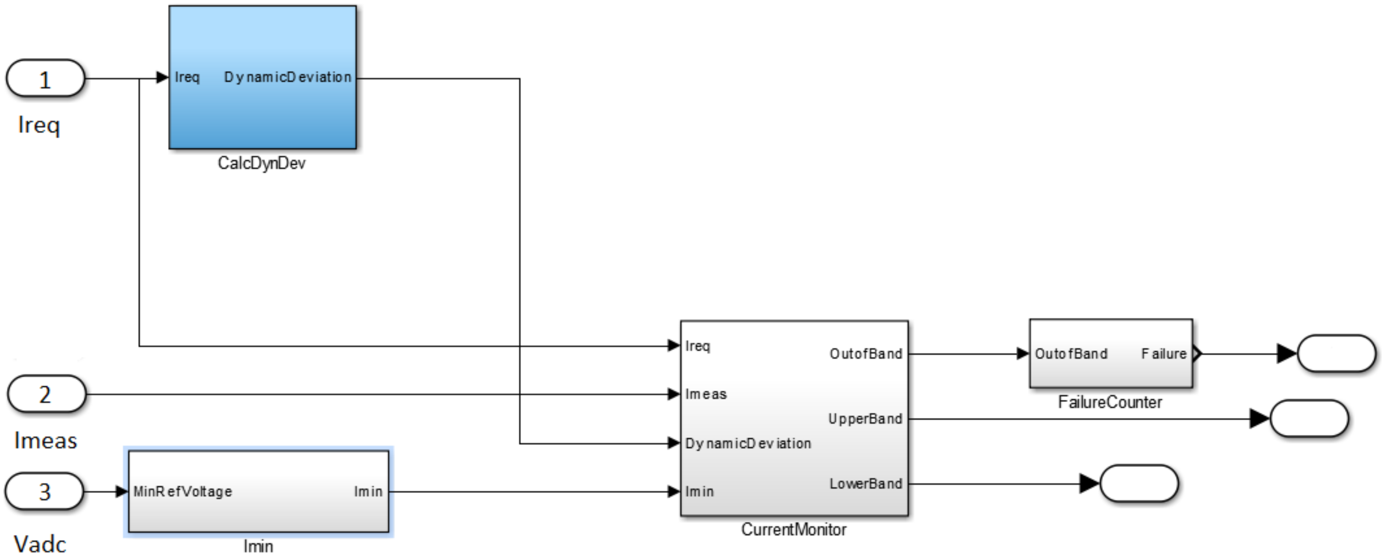
Main Driver Overload Detection:

A differential voltage comparator monitors the drain source voltage of the driver (OCF1 flag). If a certain threshold is exceeded an over current is detected and the valve stages are switched off.

See SRS 2.0 MK100 MCIV ID 1734626 and 1736961 for further information.

4.2 Appendix Valve current supervision

This chapter describes the valve current supervisions more detailed. The following figure shall provide a rough overview.



Block DynamicDeviation:

This block provides a supervision threshold that is adapted taking response time and controller parameters into consideration.

Block Imin:

This block provides a minimum current that should be available assuming worst case conditions.

Block CurrentMonitor:

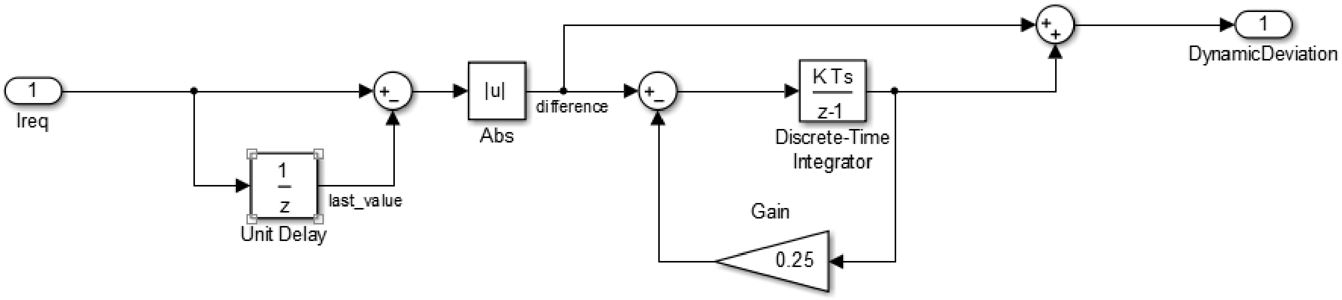
This block compares the requested current with the measured current taking the dynamic allowance into consideration.

Block FailureCounter:

This block counts failure events.

4.2.1 Calculation of the dynamic deviation

The block DynamicDeviation provides a supervision threshold that is adapted taking response time and controller parameters into consideration. The following figure illustrates the algorithm.



The algorithm implements the following equations:

y1[n] = abs(u[n]) * K * Ts/(z-1) – y1[n-1] (1)

y2[n] = abs(u[n]) + y1[n] (2)

with u[n] = Ireq[n]-Ireq[n-1], and y2[n] = DynamicDeviation

The figure in chapter "Current monitoring" illustrates an example (step response from 0 to 1500mA).

The dynamic deviation is included in the signal upper threshold.

4.2.2 Calculation of the minimum current

This block provides a minimum current that should be available assuming worst case conditions.

The following components of the electrical path are considered

- Resistance of the main driver (MD) at 220°C
- Resistance of the valve coil (coil) at 220°C
- Measured supply voltage Umin*1)

Equations:

R(theta) = R(RT)*(1+alpha*theta) (1)

Rtotal(theta) = R(MD, theta) + R(coil, theta) (2)

Imin = Umin/Rtotal(theta), (3)

Where theta is the temperature, alpha is the material constant and RT is room temperature (20°C).

Note:

*1) In case that the voltage drops below a certain threshold the pressure requesting functions are disabled; for instance AYC below 9V or EBD below 8.3V.

4.2.3 Current monitoring

This block calculates

- the upper supervision threshold,
- the lower supervision threshold
- and compares the requested current with the measured current.

Equations:

Upper threshold = Ireq * (1 + 0.05) + DynamicDeviation (1)

Where 0.05 is the steady state allowance of the current controller.

The upper threshold is limited to the maximum current as upper limit and 100mA as lower limit.

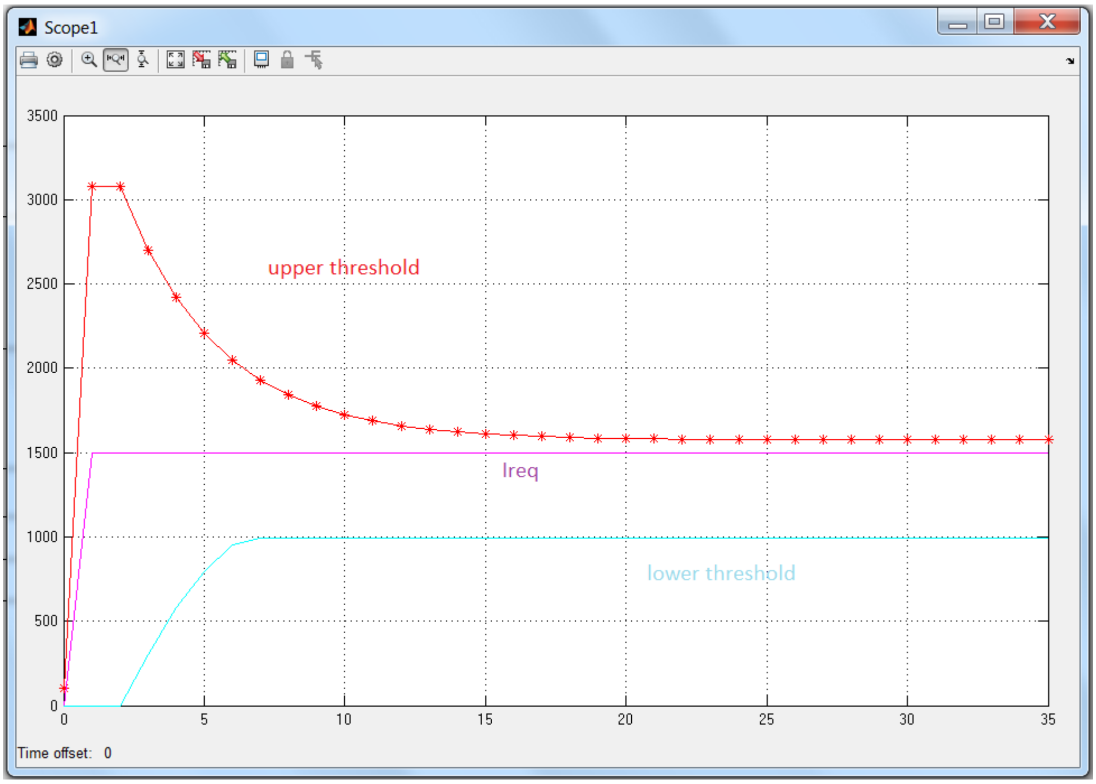
Lower threshold1 = Ireq * (1 - 0.05) – DynamicDeviation (2)

Lower threshold2 = Imin (3)

Lower threshold = Minimum(Lower threshold1, Lower threshold2, 0). (4)

A failure event is detected if the measures current is not between the upper threshold and the lower threshold.

The following figure illustrates an example (step response from 0 to 1500mA).



5 Figures

6 Tables