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ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

TESTING OF THE COMMON-RAIL PRESSURE REGULATION VALVE BY ADWIN DEVICE
TESTOVÁNÍ TLAKOVÉHO REGULAČNÍHO VENTILU COMMON-RAIL SYSTÉMU POMOCÍ ZAŘÍZENÍ ADWIN

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Assignment Master's Thesis

Institut:	Institute of Automotive Engineering
Student:	**Bc. Vojtěch Šoulák**
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Testing of the Common–rail pressure regulation valve by ADwin device

Brief Description:

The task is to perform basic tests to verify the functionality and usability of the ADwin device for testing the common–rail pressure control valve. For the implementation of the main task it is necessary to deal with the description of the common–rail system focusing on the function of the pressure control valve, study of functions and setting of boundary conditions in ADwin, definition of possible connection of ADwin to existing test stations, comparison with existing testing possibilities in development laboratory and create a test program using the ADwin device.

Master's Thesis goals:

Search of the current state of test methods of the pressure control valve
ADwin device description
Implementation of ADwin devices on a development test station

Recommended bibliography:

GUHMANN, Clemens, Jens RIESE a Klaus VON RUDEN, 2016. Simulation and Testing for Vehicle Technology: 7th Conference, Berlin, May 12-13, 2016. 1. Imprint: Springer. ISBN 978-331-9323-459.

MOLLENHAUER, Klaus a Helmut TSCHÖKE. Handbook of diesel engines. Berlin: Springer-Verlag Berlin Heidelberg 2010, 2010. ISBN 978-3-540-89082-9.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2021/22

In Brno,

L. S.

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prof. Ing. Josef Štětina, Ph.D.   doc. Ing. Jaroslav Katolický, Ph.D.
Director of the Institute   FME dean

ABSTRAKT

Tato diplomová práce se zabývá rozšířením testovacích možností vývojové stanice pomocí zařízení ADwin. Hlavní částí diplomové práce je navržení přídavného okruhu testovací stanice a naprogramování testu pro tlakový regulační ventil. V další část se diplomová práce zabývá předpokladem stavu komponent regulačního ventilu po testování. Při porovnání tohoto předpokládaného stavu a reálném stavu po testování je ověřeno správné naprogramování testu a správná funkce nově navrženého okruhu.

KLÍČOVÁ SLOVA

Vznětový motor, Common-rail systém, tlakový regulační ventil, testovací stanice, testování regulačního ventilu, zařízení ADwin, ADbasic, kontaktní únava, PWM, ECU

ABSTRACT

This diploma thesis deals with the extension of the testing possibilities of the development test bench using the ADwin device. The main part of the diploma thesis is the design of an additional circuit of the test bench and test programming for pressure control valve. Following part of the diploma thesis deals with the assumption of the pressure control valve components condition after testing. When comparing the expected condition and actual condition after testing, the correct test programming and the correct function of the newly designed circuit are verified.

KEYWORDS

Diesel engine, Common-rail system, pressure control valve, test bench, pressure control valve testing, ADwin device, ADbasic, contact fatigue, PWM, ECU

BIBLIOGRAPHICAL REFERENCE

ŠOULÁK, Vojtěch. *Testování tlakového regulačního ventilu Common-rail systému pomocí zařízení ADwin*. Brno, 2022. Dostupné z: https://www.vutbr.cz/studenti/zav-prace/detail/140153. Diplomová práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Ústav automobilního a dopravního inženýrství. 55 s. Vedoucí práce Pavel Kučera.

ČESTNÉ PROHLÁŠENÍ

Prohlašuji, že tato práce je mým původním dílem, zpracoval jsem ji samostatně pod vedením doc. Ing. Pavla Kučery, Ph.D. a s použitím informačních zdrojů uvedených v seznamu.

V Brně dne   ....

Bc. Vojtěch Šoulák

PODĚKOVÁNÍ

CONTENT

INTRODUCTION

One of the possible ways to transport people or cargo from point A to point B is by car. Nowadays, this type of vehicle is a very complex machine, in the production of which many scientific disciplines are involved. One of the main parts of the car is the engine. There are a relatively large number of engine types that are used to power cars. This diploma thesis focuses on the component that is located in the diesel type of engine. One of the options for supplying fuel into the combustion chamber of the diesel engine is the Common-rail injection system.

The word "common" and "rail" describe important features of this system. This feature is the common pressure accumulator (rail) for all fuel injectors. The common-rail system consists of a large number of components, where each component has its own system function. One of the functions needed for the correct operation of the system is the regulation of the rail pressure. Part of this function is provided in the common-rail system by means of regulation valve, which is the subject of this diploma thesis. In German, this component is called "Druckregelventil" and in Czech "Regulační ventil", but in the diploma thesis, this component is referred to as a pressure control valve.

The company Bosch Diesel s.r.o., which is the ordering party of this diploma thesis, deals with the production of the common-rail system components. A diploma thesis assignment from the Bosch company was to implement the ADwin device into the development test bench. Where the implementation should contribute to expanding the capabilities of the test bench designed for pressure control valve testing. To properly perform this implementation, it is necessary to obtain the information about the ADwin device and the function of the pressure control valve in the common-rail system. The next phase of the diploma thesis is devoted to understanding the function of the original layout of the test bench. At the end of the thesis, it is verified whether the desired result has been achieved. As a verification, a trial test is performed with the new layout, which confirms or refutes the correctness of the implementation.

1 COMMON-RAIL SYSTEM

The common-rail system is a type of direct fuel injection system that is used in diesel engines. This type of system separates the injection of the fuel and the pressure generation. Therefore, the high-pressure pump's delivery phase is not coupled with the injection timing or the injected fuel quantity. This separation also provides the injection system with independence to speed or load [1].

The high-pressure pump delivers the fuel under the injection pressure to the rail. Injectors and the rail are connected, by short high-pressure lines. Injection of the fuel to the combustion chamber is actuated by the piezoelectric or the solenoid injectors. This electrically controlled injectors bring to the system advantage of flexible shape of the injection characteristic [1].

Common-rail system can be divided to subsystems:

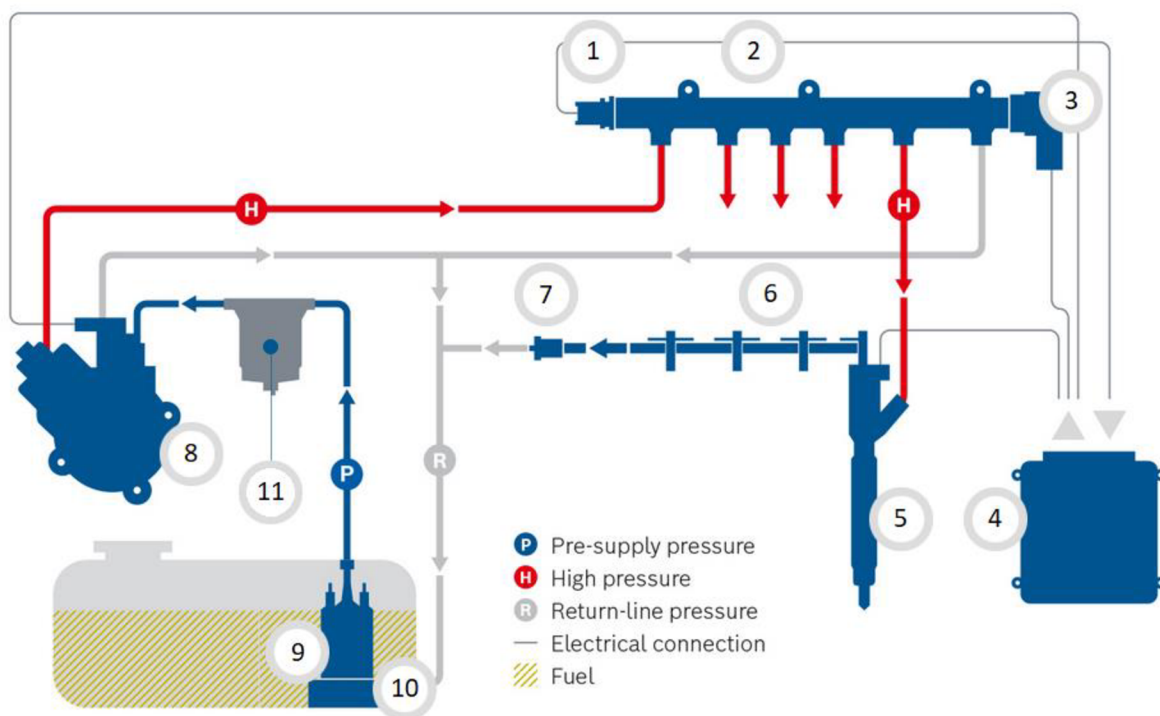- o High-pressure circuit.
- o Low-pressure circuit.

Figure 1 Common-rail system CRS2-25 – 1-Rail pressure sensor; 2-High-pressure rail; 3-Pressure control valve; 4-Electronic engine control unit; 5-Injector; 6-Fuel-return line; 7-Non-return line; 8-High-pressure pump; 9-Electric pre-supply pump; 10-Pre-filter; 11-Fuel filter [11]

1.1 LOW PRESSURE SYSTEM

The low-pressure circuit starts with an electric pre-supply pump, which is located in the fuel tank. The pre-supply pump switches on when the starting process begins. The pump starts generating necessary pressure in the low-pressure circuit and starts continuously delivering fuel to the high-pressure pump. From the high-pressure pump flows the excess fuel, controlled by overflow valve, back to the fuel tank. To avoid damage of the high-pressure pump or injectors from impurities in the fuel. The low-pressure system is equipped with fuel filter and pre-filter. In systems with suction side fuel delivery control is the quantity of fuel, which is delivered to the high-pressure pump, regulated by metering unit (MeUn), located in the high-pressure pump's low-pressure stage [1].

1.2 HIGH PRESSURE SYSTEM

From the low-pressure circuit is the fuel delivered to the high-pressure pump, where the fuel is compressed and trough the high-pressure line is the compressed fuel transfer to the rail. Where the function of the rail is not only for the compressed fuel accumulation, but also to limiting the pressure oscillation caused by the pulsing of the fuel delivery and by the fuel injection. Therefore, measurement of the actual fuel pressure in the rail, metered by rail pressure sensor, is more precise. Afterwards is the fuel distributed to the injectors[1].

Current fuel pressure is variable used for pressure control in high-pressure system. There are used three modes of pressure control in the common-rail system:

- o High-pressure side control.
- o Suction side control.
- o Suction and high-pressure side control [1].

1.2.1 HIGH-PRESSURE SIDE CONTROL

This method is based on the maximum amount of the fuel delivery from the high-pressure pump, without considering the fuel requirement. The rail pressure regulation is actuated by means of the pressure control valve (PCV), where the excess fuel flows through the valve and back to the low-pressure circuit. The PCV allows system to rapidly control the rail pressure and by circulating the fuel from the high-pressure circuit to the low-pressure circuit, the fuel temperature rises. The disadvantage of the high-pressure side control is from an energetic point of view, due to the maximum delivery rate of the high-pressure pump [1].
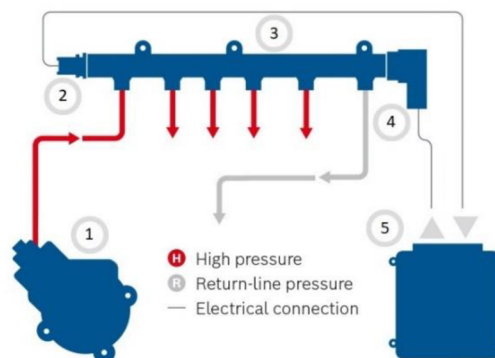

Figure 2 High-pressure side control - 1-High pressure pump; 2-Rail pressure sensor; 3-Rail; 4-Pressure control valve; 5- Electronic engine control unit

1.2.2 SUCTION SIDE CONTROL

This type of pressure control maintains the required rail pressure by controlling the fuel supply on the low-pressure side of the high-pressure pump. The quantity of the fuel delivery is controlled by MeUn. The suction side control has lower power consumption then the high-pressure side control, due to the low fuel delivery to the high-pressure pump. For the safety of the system, the pressure limiting valve is mounted on the rail, which is opened when there is the unwanted rise of the pressure in the rail [1].

Figure 3 Suction side control - 1-High pressure pump; 2-Metering unit; 3-Rail pressure sensor; 4-Rail; 5-Pressure limiting valve; 6- Electronic engine control unit

1.2.3 SUCTION AND HIGH-PRESSURE SIDE CONTROL

There is possibility to control the low-pressure side of the high-pressure pump and the PCV mounted on the rail of the high-pressure side. The system by controlling the low-pressure and the high-pressure side uses both of their advantages to perform more effectively and accurately. The possibility of controlling both sides of the system can be used, when the engine is cold. The system by controlling the low-pressure side delivers higher quantity of the fuel then it is required. Thus, the excess fuel flows through the PCV back to the fuel tank and the system is heated faster [1].

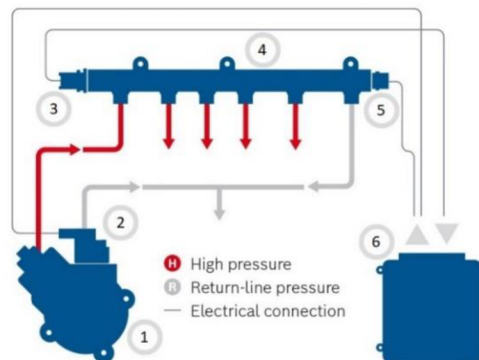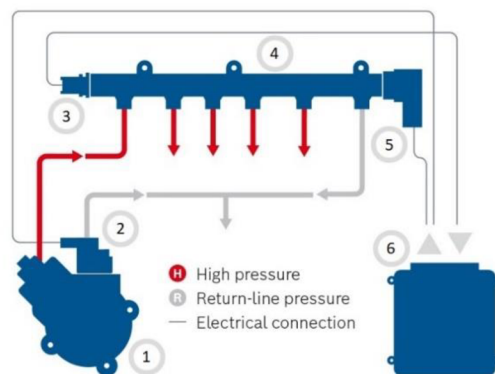*Figure 4* Suction and high-pressure side control - 1-High pressure pump; 2-Metering unit; 3-Rail pressure sensor; 4-Rail; 5-Pressure control valve; 6- Electronic engine control unit

2 PRESSURE CONTROL VALVE

The PCV is one of the actuators of the common-rail injection system. The valve is mounted on the rail on the high-pressure side. This actuator is driven by the current I [A] with a proportional corelation between the current and the system pressure. The pressure regulation is driven by the electronic control unit (ECU) through the pulse-width modulated (PWM) signal [1][2].
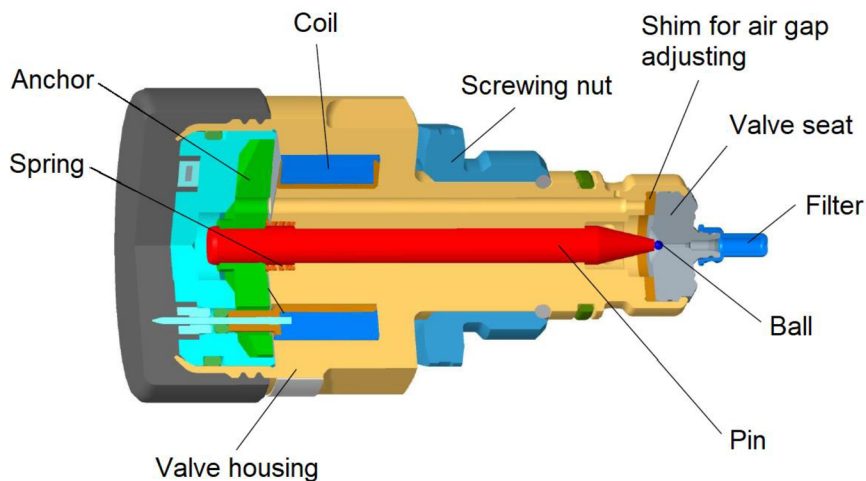
Figure 5 PCV cross section: main components [1]

2.1 PCV TYPES MANUFACTURED IN BOSCH COMPANY

The Bosch company manufactures two types of the PCV. There is the PCV with spring above the anchor, which is closed when there is no current supply and the PCV with spring below the anchor, which is open when there is no current supply [2].

2.1.1 FUNCTION OF THE CURRENTLESS OPEN PCV

Without the current supply to the solenoid, the PCV is in the open state, due to the spring. The spring pushes the anchor with the pin further from the valve housing and creates the air gap between the ball and the valve seat of the valve body [2].

When the solenoid is supplied by the current, the PCV is in the closed state. Activated solenoid creates a magnetic field in the valve housing. Thus, a magnetic force is created and pulls the anchor with the pin closer to the valve housing and narrows the air gab between the anchor and the valve housing. The created force, transmitted through the pin and starts pressing the ball against the valve seat. In order to close the PCV, the magnetic force must be higher than the rail pressure force and the force generated by the spring [2].
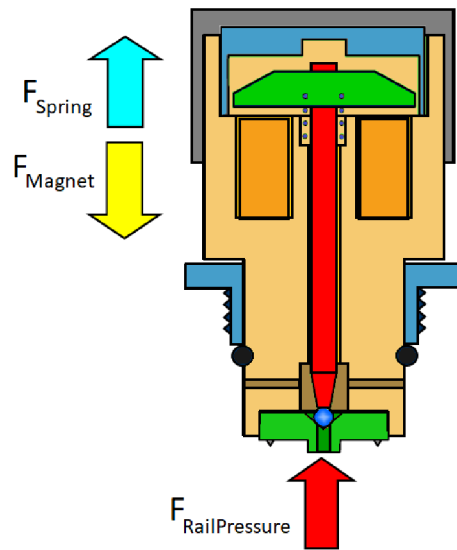
Figure 6 Currentless open PCV [2]

2.1.2 FUNCTION OF THE CURRENTLESS CLOSED PCV

For maintaining the system pressure in the rail, the solenoid is activated by electrical current. Same as in case of the currentless open PCV, the magnetic force is created. The magnetic force, together with the force created by the spring acts against the rail pressure force and closes the PCV [2].

This type of PCV uses the limp home function. When the limp home function is active, only the spring pushes the anchor, pin and ball against the valve seat and closes the PCV. In this case, the rail pressure is maintained below the system pressure. This function allows the vehicle to continue driving in limited conditions to the closest service station [2].

Figure 7 Currentless closed PCV [2]

2.2 HIGH-PRESSURE AND LOW-PRESSURE CONNECTION

The PCV is a high-pressure side actuator of the common-rail system. This actuator regulates the system pressure by connecting the high-pressure circuit and low-pressure circuit [1].

The valve is mounted on the rail by using the screwing nut. By tightening the nut, the bite edge of the valve seat is pressed against the contact area of the rail. This contact seals the high-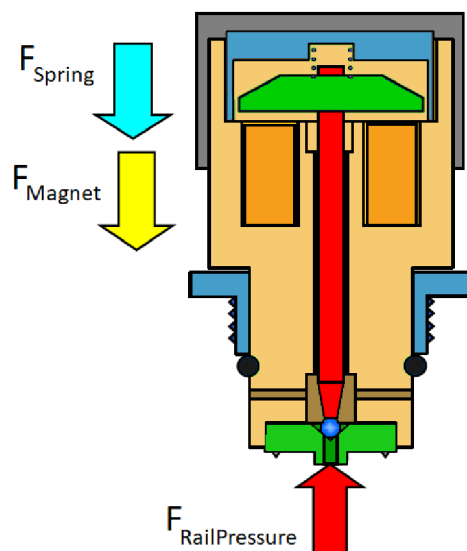pressure circuit. Thus, the PCV works as a pressure plug when it is in closed state. The pressure regulation is governed by altering a cross section between the valve seat and ball. By increasing the cross section, the circuits are connected and fuel flows through the valve into the low-pressure circuit. The PCV uses the o-ring located between the screwing nut and valve body to seal the low-pressure circuit. To prevent damage to the mechanical parts of the PCV by impurities in the fuel, the PCV inlet is equipped with a filter [2].
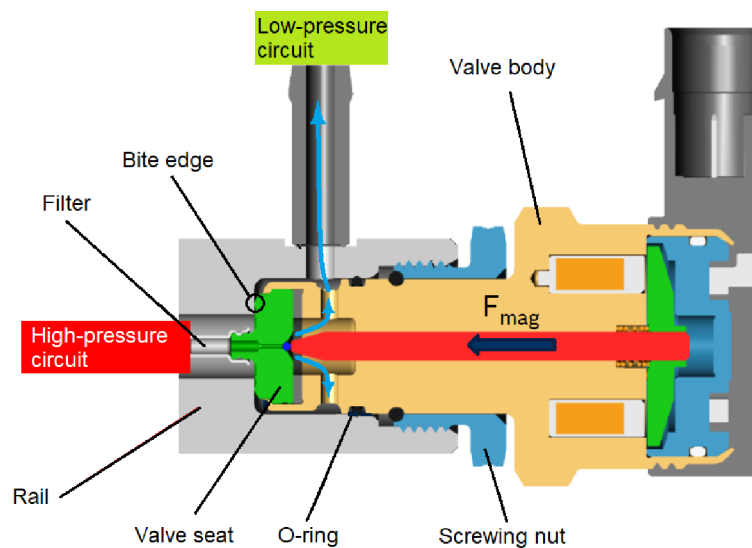
Figure 8 Rail sealing [2]

2.3 PCV SET UP

When assembling all the components together, the PCV must be set up to ensure proper function of the whole mechanism. The only adjustable parameter that can be adjusted when the PCV is assembled is working air gap (WAG). The value of the magnetic force depends on the current supply and the distance between the coil and the anchor, which is called WAG [2].
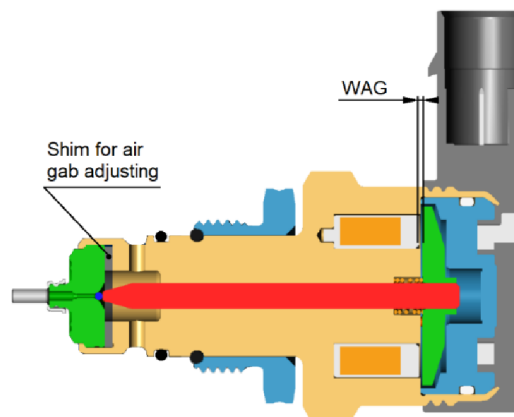
Figure 9 PCV cross section: Working air gap [2]

The WAG is adjusted trough measurement of the magnetic force during the assembly of the PCV on the production line. Based on the measurement, a suitable shim is selected for the air gap adjusting. After the assembly, the functional test is performed, which checks the pressure at a certain supply current (*Figure 10*) [2].
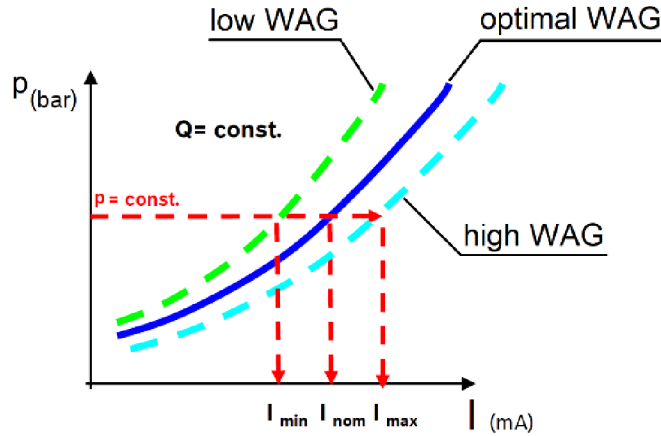
Figure 10 WAG adjustment: p/I characteristic

The reason why the low WAG is not used for the PCV set up is based on the shape of the WAG and magnetic force corelation (*Figure 11*). If the low WAG is used as the setup, less supply current is required to generate the magnetic force, but the magnetic force is in this area more sensitive to the position change of the anchor. This means a greater instability risk in the PCV control. On the other hand, when the high WAG is used as the setup, the magnetic force sensitivity is advantageous, but the value of the supplied current is too high to achieve required magnetic force. By setting the optimal WAG, the optimal magnetic sensitivity and the supply current value are ensured [2].
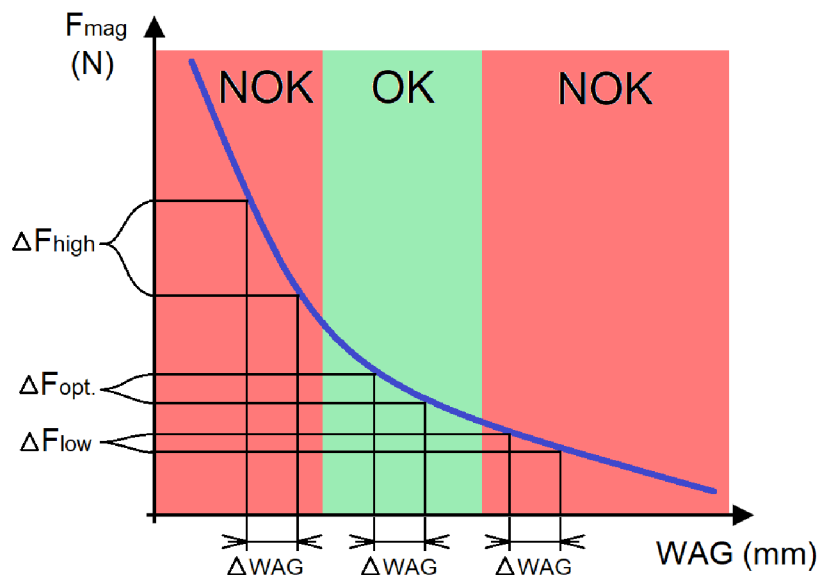
Figure 11 WAG adjustment: Magnetic force-WAG dependence

2.4 PCV CONTROL

The PCV control belongs to the so-called electronic diesel control (EDC) system of the vehicle. It is an electronically controlled system that oversees diesel engine fuel-injection. The EDC system can be subdivided into three areas:

- o **Sensors and desired-value generators** - rail pressure sensor (RPS), fuel temperature sensor, inductive rpm sensor, accelerator-pedal sensor.
- o **Electronic control unit** (ECU).
- o **Actuators** - PCV, MeUn [3][4].

The PCV is controlled by supply current regulation using a PWM signal.

2.4.1 PWM SIGNAL

The pulse width modulation (PWM) signal is one of the possible outputs of the ECU microcontroller. It is a digital square wave signal used in analog circuits control [3] [4].

The PWM signal is a constant-frequency signal with a variable on-time. The ratio of the variable on-time and frequency is called the duty cycle, which is often expressed as a percentage value (from 0% to 100%). By setting the duty cycle, in the PWM signal, it is determined for how long the controlled analog circuit is switched on in the repetitive fixed time period [5].
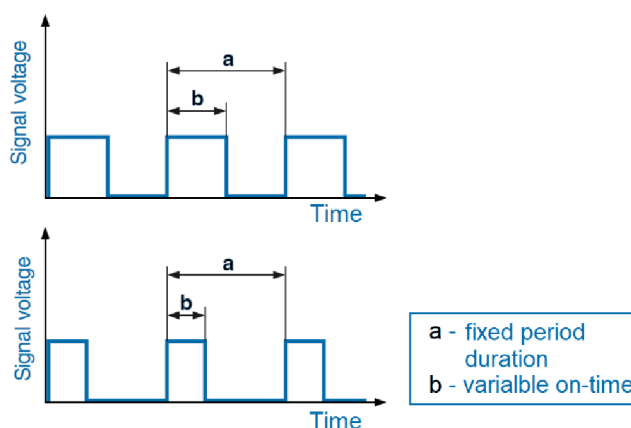
Figure 12 PWM signal description

2.4.2 EDC SYSTEM CONTROL

The PCV control by the EDC system consist of the fuel pressure setpoint calculation, the fuel pressure governor and the fuel pressure monitoring [2].

If there is a situation where it is necessary to regulate the system pressure using the PCV, the setpoint of the fuel pressure is by means of the ECU calculated. The setpoint is calculated based on the inputs from sensors that monitors the present operating state of the vehicle. These inputs from the sensors are compared to the required values which are provided by the programmed maps in the microcontroller. These maps by obtaining the information about the average engine speed and the injection fuel quantity provides required value for the present operating state of the vehicle. The difference between the inputs from the sensors and the

required values from the maps adjust the fuel pressure setpoint, which is sent to the fuel pressure governor [2].

The PI-governor is used as the fuel pressure governor. This governor uses the current feedback and calculated setpoint to adjust the value of the duty cycle. The current feedback is provided from the high-performance driver circuit that supplies the PCV with current from the vehicle battery. The duty cycle of the PWM signal regulates the current supply for the PCV by turning the driver circuit on and off, in the repetitive fixed time period [2][3][4].
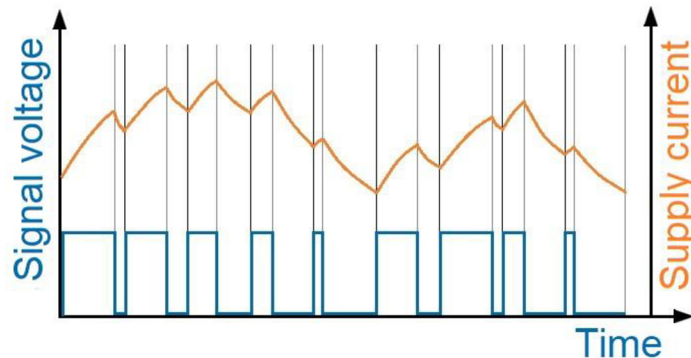
Figure 13 PWM signal: Current control

2.4.3 OUTPUT BATTERY CORRECTION

Every output from the ECU is battery voltage corrected. This means that the proper actuator control is ensured in any battery condition. For the correction according to the battery condition, the information about the reference battery voltage and the actual battery voltage are used to adjust the output duty cycle [2].

2.5 RANGE OF PCV USAGE IN COMMON-RAIL SYSTEM

For this chapter was used information source [2].

Since the PCV connects the high-pressure circuit to the low-pressure circuit, it is possible to regulate the common-rail injection pressure together with the MeUn. The cases of the PCV use for the system pressure regulation are:

- o   Active rail pressure limitation.
- o   MeUn dynamic pressure decrease support.
- o   Engine start.
- o   Fuel heating.
- o   Active limp home mode (Currentless closed PCV) [2].

If there is a failure situation which would lead to an uncontrollable rail pressure increase (for example, the MeUn jammed in the open position), a rail pressure limitation mode is activated. The PCV operates as the safety element of the system and regulates the rail pressure in pressure limitation mode. This mode is limited by the number of PCV openings where the number is defined in the lifetime table of the PCV [2].

One of the main functions of the PCV is to increase the dynamic of the system pressure regulation by supporting the MeUn. In the case of the low idle or the engine overrun it is necessary to quickly decrease the rail pressure. By using the dual control, faster regulation of the rail pressure is achieved than it would in the case of the only MeUn control mode (*Figure 14*) [2].
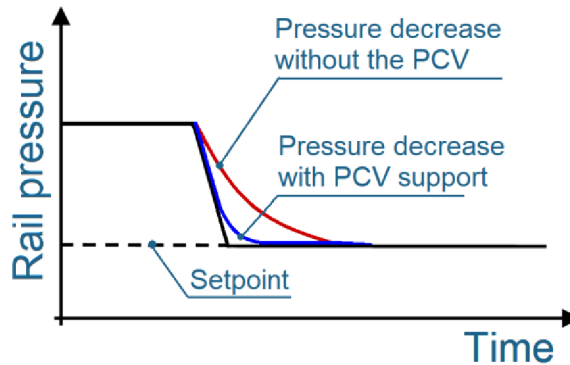
Figure 14 Rail pressure control: PCV support

Most of the time is the common-rail system controlled by the MeUn on the low-pressure side of the high-pressure pump. The MeUn controls the system in the range of high injection quantities and high rail pressure. The PCV controls the system when the engine is started and when the fuel needs to by heated. The system is also controlled by the PCV, when the limp home function is active. In the range of the small injection quantities is the system controlled by the MeUn together with the PCV [2].
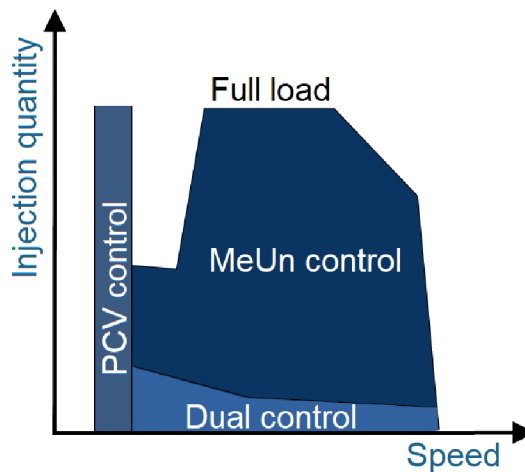
Figure 15 PCV and MeUn control map

3 TEST BENCH

The PCV is a very complex hydraulic element that requires precise setup. Due to its function as one of the safety elements of the common-rail system, great demands are placed on the PCV for its precise operation. The PCV needs to be tested to verify its correct setup and operation stability. For this reason, the Bosch company has developed test benches that can verify these requirements. The test bench contains an equipment that can be used to simulate the operating condition of the PCV without mounting it on the engine. This testing solution allows to execute the variety of tests in a secure environment. (*Figure 16*)
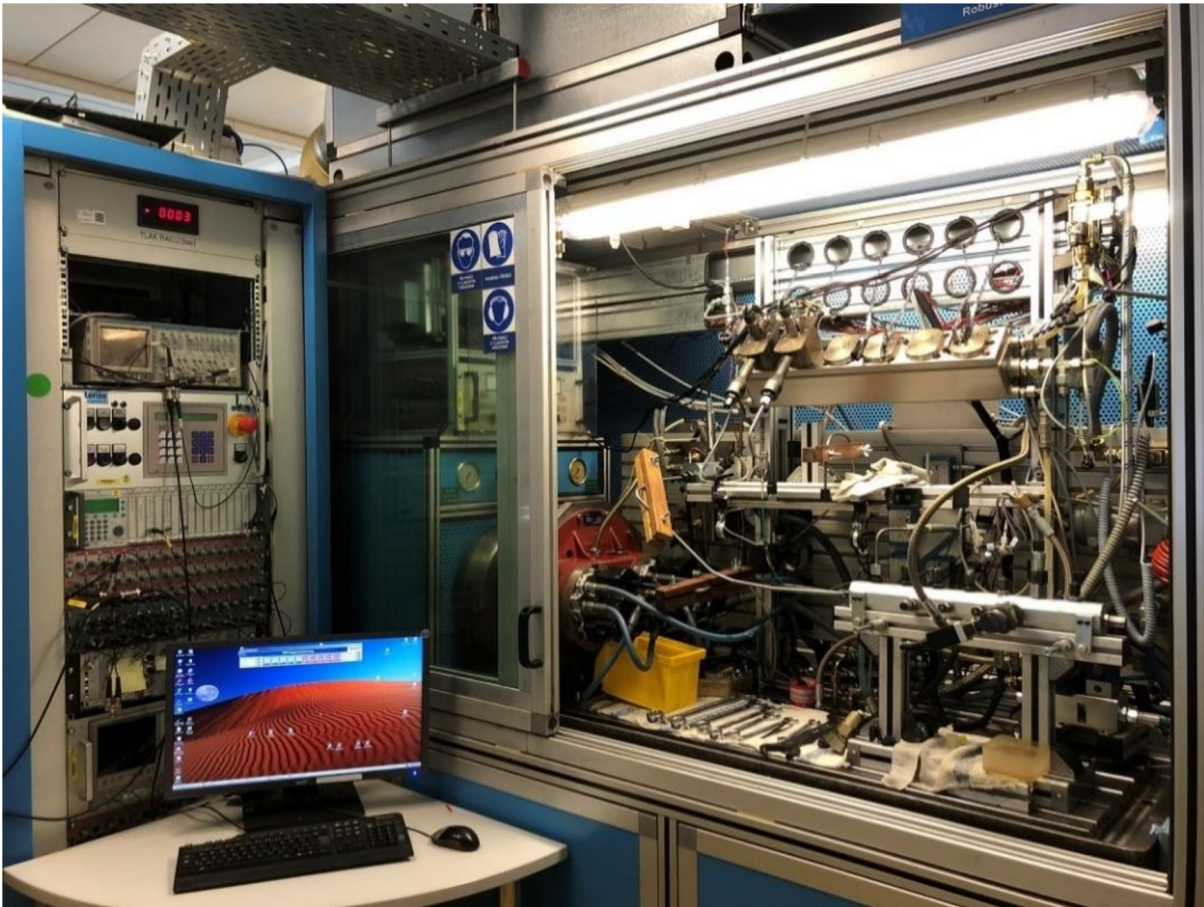
Figure 16 Bosch test bench T04

The test bench consists of two parts:

- o Testing area.
- o Control panel.

The testing area contains all the actuators and sensors. There is also a hydraulic layout placed in the testing area. For the operator safety, the testing area is covered with safety glass. By means of control panel, the test bench actuators and hydraulic layout can be controlled. There is an output signal collector from the test bench sensors on the control panel. The collector allows monitoring of the measured variables from the testbench testing area [2].

To define the test parameters, the test bench uses the development environment from a visual programming language LabVIEW. Using the LabVIEW software, the control environment

was created. By means of control environment, the test parameters can be defined by the test bench operator [2].

3.1 TEST BENCH LAYOUT DESCRIPTION

For a better understanding, the test bench layout is described according to the *Figure 17*.
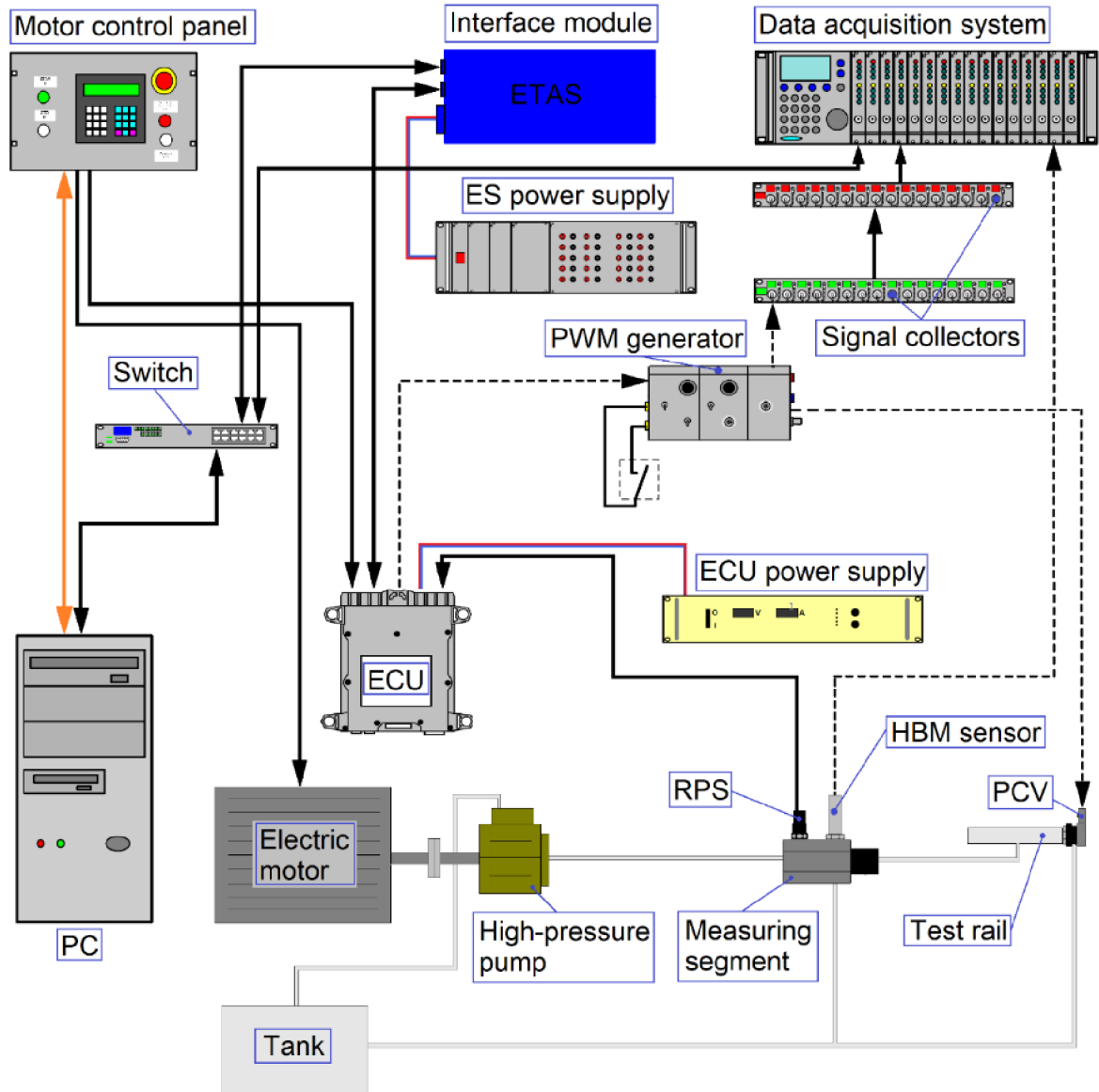
Figure 17 Test bench layout

The parameters for the required test are defined in the LabView control environment. The LabView control environment communicates with the ECU via INCA software, which is the software published by ETAS company used for the development of the ECUs. Due to the impossibility of connecting the PC directly to the ECU via Ethernet cable, the ETAS interface module is used in the test bench layout. This interface module connects the PC via Ethernet cable and ECU via ETK cable with the ECU connector. The set parameters in LabView are therefore sent to the ECU, where are processed by a programmed logic in the ECU

microcontroller. The PCV is directly controlled by the ECU integrated driver circuit, which is powered by ECU power supply. According to the received parameters processed in the microcontroller, the ECU regulates the current supply to the PCV by the duty cycle of the PWM output signal. The regulated current is supplied to the PCV through a PWM generator. For this layout, the PWM generator is used only because of its signal output shunt, due to which is possible to measure the supply current from the ECU to the PCV. Voltage signal from the PWM generator is sent through the signal collectors to a data acquisition system. To the data acquisition system is also connected a pressure HBM sensor from a measuring segment, which measures pressure from the test rail. Processed signals from the acquisition system are sent via a Switch to the PC. For the ECU to function properly, feedback on rail pressure and electric motor speed are required. The rail pressure feedback is provided by a test bench RPS and the electric motor speed feedback by motor control panel. To generate pressure in the test rail, there is a high-pressure pump in the layout, which is driven by electric motor with adjustable speed [2].

3.2 STANDARD TESTING OF THE PCV

Standard tests performed on the test bench are intended to verify and validate the stability of the PCV pressure regulation. For these tests is used the test bench layout, which is described in the previous chapter.

The essence of these tests is based on plotting a dependence of two parameters, from which is possible to evaluate whether the entire operating spectrum is stable. There are several adjustable parameters, which is used to create the dependence:

  o Current [A].
  o Flow rate [l/h].
  o Pressure [bar].

One of these parameters is set as a variable parameter and one as a constant parameter. By changing the variable parameter, it is possible to record the correlation between the variable parameter and its dependent parameter. The transition between the minimal and the maximum value of the variable parameter is performed smoothly during standard testing. Since the goal is to observe the stability of regulation, it is not necessary to perform the jump changes of the variable parameters. These plotted relationships between the parameters are then evaluate according to defined tolerance field. One of the possible outputs of the standard testing is p/I characteristic [2].

3.2.1 P/I CHARACTERISTIC

The p/I characteristic figure the relationship between the pressure of the test bench rail and the current supplied to the PCV. The current is set for the p/I characteristic as the variable parameter. During the current change, the test bench maintained the constant flow rate from the high-pressure pump. From the HBM sensor and the PWM generator shunt is recorded a progress of the current and the pressure. Progressions are processed in the test bench data acquisition system and plotted as the p/I characteristic (*Figure 18*) [2].
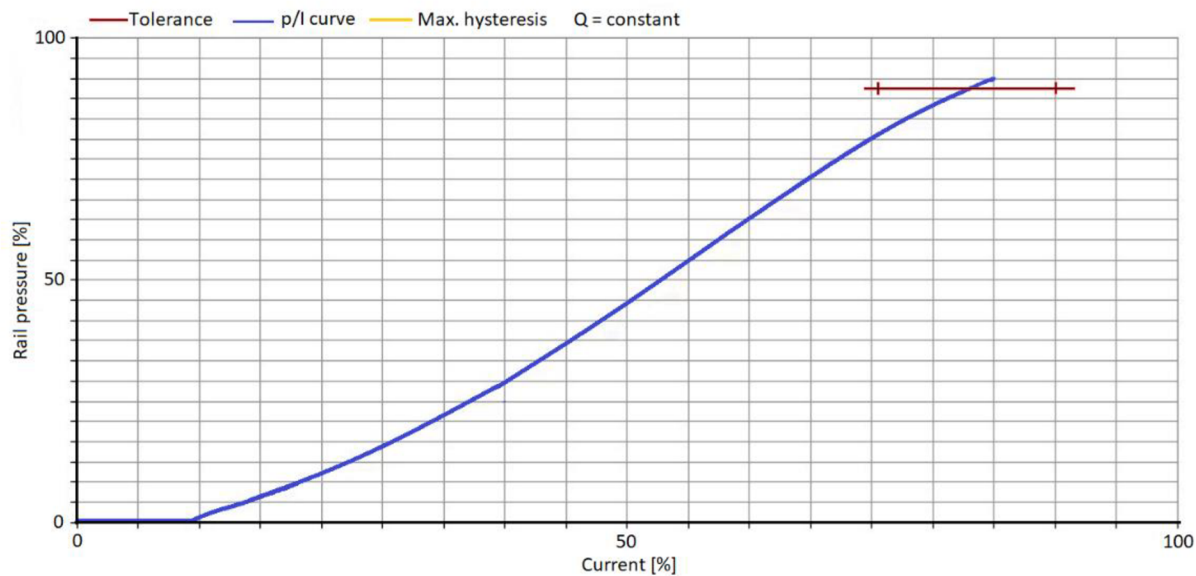
Figure 18 p/I characteristic example

After plotting the p/I characteristic, the development of the dependence is observed to see if any irregularities occur. The main observed part of the dependence is the area of the working point, which is monitored in the defined pressure value. The working point must be within the defined tolerance field. If the working point is within the defined tolerance and the dependence shows no signs of irregularities, the PCV is evaluated as OK [2].

4 PROBLEM DESCRIPTION

The test benches were specially built for standard testing of the PCV. The essence of these tests is slow nondynamic change of the parameter and for this purpose the layout of the test bench was designed [2].

The test bench reliably manages to perform all the standard tests of the PCV. The problem arises when there is requirement for the unregular test, which contents fast jump change of the supply current. The layout of the test bench is not designed for these types of changes and the execution of the jump change is a lot slower than is required in the test.

4.1 COMPARISON TEST

To provide a visual example of the problem with the fast jump change, there was performed a comparison test with following boundary conditions:

- o   Number of cycles: 1
- o   Current low: 0 mA
- o   Current high: 1800 mA
- o   Current hold time: 2 sec

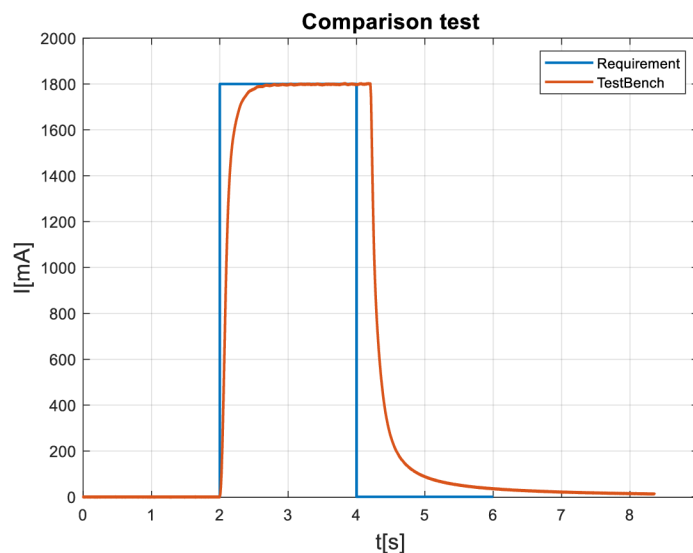The comparison test was according to the boundary conditions defined in the LabView control environment and executed by the test bench. The time record of the current development was recorded by means of oscilloscope and the obtained data were processed using the MatLab software (*Figure 19*).

Figure 19 Comparison test plot

A comparison of the required jump change and jump change executed by the test bench showed that the step-up and the step-down of the current is performed slower than required. In the case of step-down change, the current failed to reach the zero value in the recorded time window. There has been observe a delay of the step-up change (to 1800 mA) compared to the required shape. The delay is partly due to the design of the test bench layout, which is not setup to dynamic changes. This reason for the delay also reflects on the step-down change (to 0 mA). Another cause of the delay is due to a software limitation of the minimum ramp-up and ramp-down value that can be entered in the control environment of the test bench. The

minimal value that could be entered in the control environment is 0.1 s (*Figure 20*). Thus, the step-up change is partly executed according to definition in the control environment, but the time value specified in the ramp-up shifts the beginning of the step-down change and creates another delay.
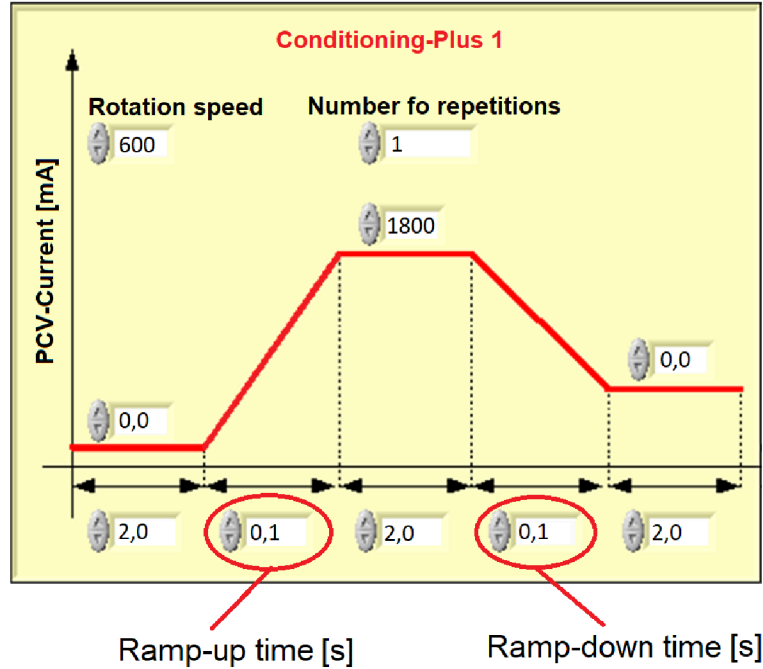
Figure 20 LabVIEW control environment: Conditioning

For this reason, it needs to be added a new layout to improve existing layout of the test bench. The new layout will help the test bench to execute the fast jump changes and expand the options of the test bench.

5 ADLAYOUT

The newly designed layout consists of two parts:

- o Additional external circuit
- o Original test bench layout

Parts of the original test bench layout, such as the hydraulic layout, were used to the new layout assembly. There has been a new additional external circuit created that can be connected to the original layout of the test bench. The reason for creating an external type of circuit was due to the possibility of connecting the circuit to other test benches. Therefore, expand the application of the newly designed layout. For better orientation, the two parts of the new designed layout together were named ADlayout.

For a better understanding, the ADlayout is described according to the (*Figure 21*).

Figure 21 ADlayout

The ADlayout contains its own power supply to supply the current for the PCV control system. The PCV is not powered directly from the power supply, due to its need of supply current regulation. For this reason, the ADlayout contains the EFS regulation module. The EFS module is directly connect to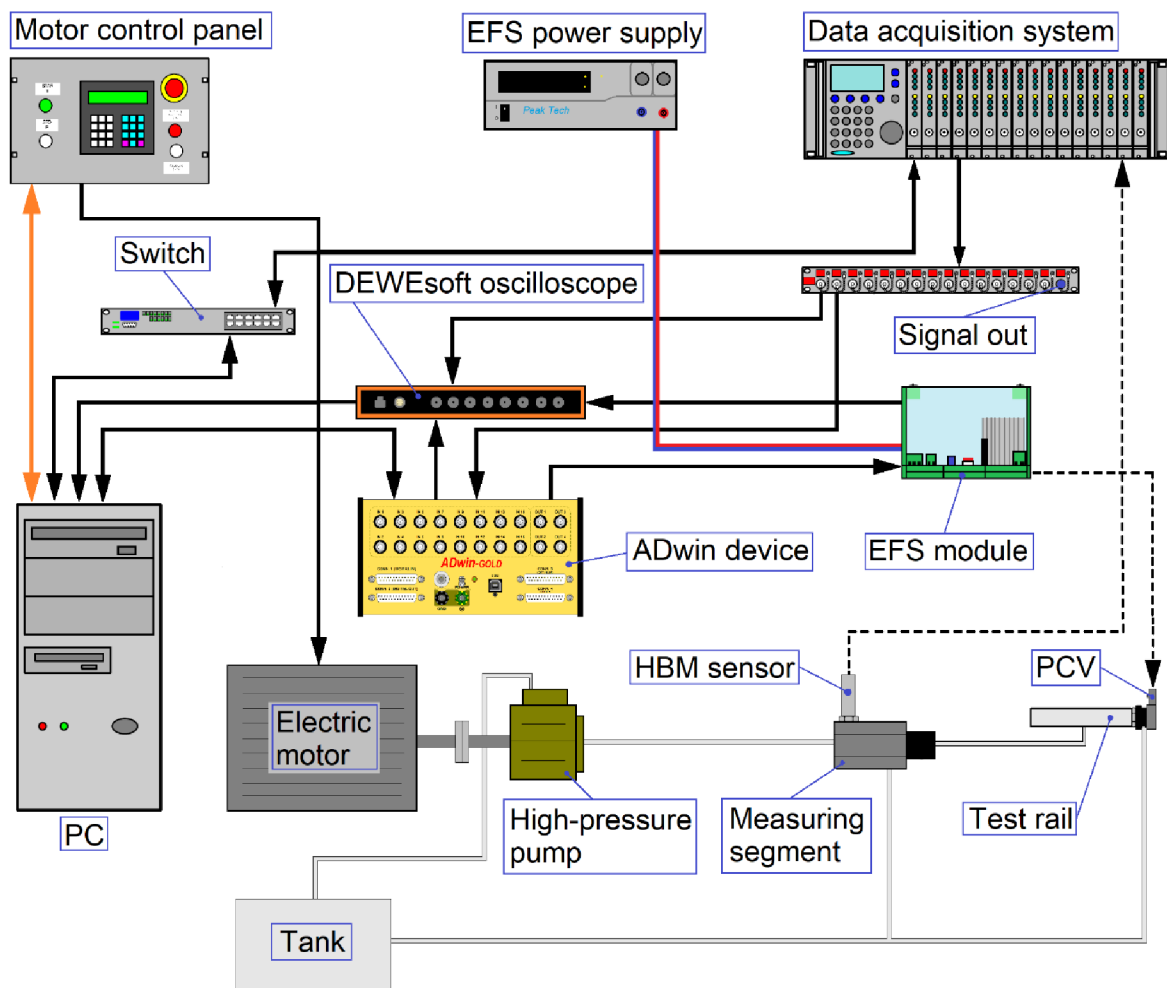 the PCV. To correctly regulate the current for the PCV, the EFS module needs to receive the setpoint, the target regulation value of the current. The setpoint is a signal from 0 to 5 V, which sets the regulation of the current from 50 mA to 5 A. Due to this requirement the ADlayout is equipped with programmable device, ADwin. The ADwin device is programmed by the integrated development environment ADbasic. By means of ADbasic is written the code, according to which the ADwin sets the setpoint for the EFS module. The ADwin device can also process data in real-time which are provided from the test bench sensors. Therefore, the ADwin can response to the feedbacks from the test bench. To receive feedback about the pressure from the test rail is ADwin connected by the cable with BNC connectors to the test benches signal out panel.

To properly simulate the exact conditions on the rail, the test bench uses the high-pressure pump to deliver the ISO fluid (substitute for the diesel fuel) to the test rail. The delivery of the ISO fluid to the test rail is controlled by the speed of the test benches electric motor that drives the high-pressure pump.

6 ADWIN SYSTEM

It is a programmable, real-time processing device which allows processing of the data from a signal input in a specified time. The processed data can be used to control the actuators by means of a signal output. The ADwin connects physical parameters measured by sensors with actuators, without using a PC. The system is optimized for processes which need very short process cycle times. This can be used in very fast digital closed-loop control applications or very fast open-loop control systems [6].

Programmability of the ADwin device brings variety of the control options to the ADlayout. Its fast processing of the data will allow the ADlayout to response quickly on feedback from the test bench. Because of this possibility is the ADwin device used as a main control part of the ADlayout.

6.1 ADWIN

The ADwin hardware consist of a central processing unit (CPU), analog-to-digital converter (ADC) and digital-to-analog converter (DAC). There can be found a digital signal processor (DSP) and floating-point unit (FPU) in the central processing unit [6].
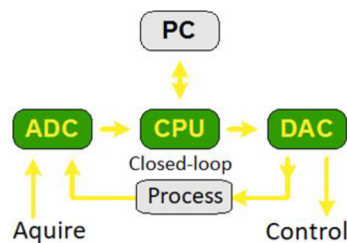
Figure 22 Closed-loop control with ADwin [10]

6.2 ADBASIC

The ADbacis is the programming tool under the Windows for the ADwin system. The ADbasic allows to create special measurement, open-loop, or closed-loop control application. The ADbasic controls ADwin hardware, by extended BASIC syntax source code, and implements tasks into the processes [7].

To perform required measurement or system control using the ADwin device, it is necessary to compile the binary code in the device. This binary code contains the logic according to which the measurement or control is governed. The binary code is programmed by means of the ADbasic development environment. In addition to programming, it is possible to start, monitor and stop the process [7].

6.2.1 ADBASIC DEVELOPMENT ENVIRONMENT

The development environment consists of windows and bars that helps with the code programming. The basic ones are shown in the *Figure 23*.

Figure 23 ADbasic development environment

The main part of the development environment is the source code window. Within this window, the code is written using the integrated libraries, macros and commands. For better orientation in the code, each lin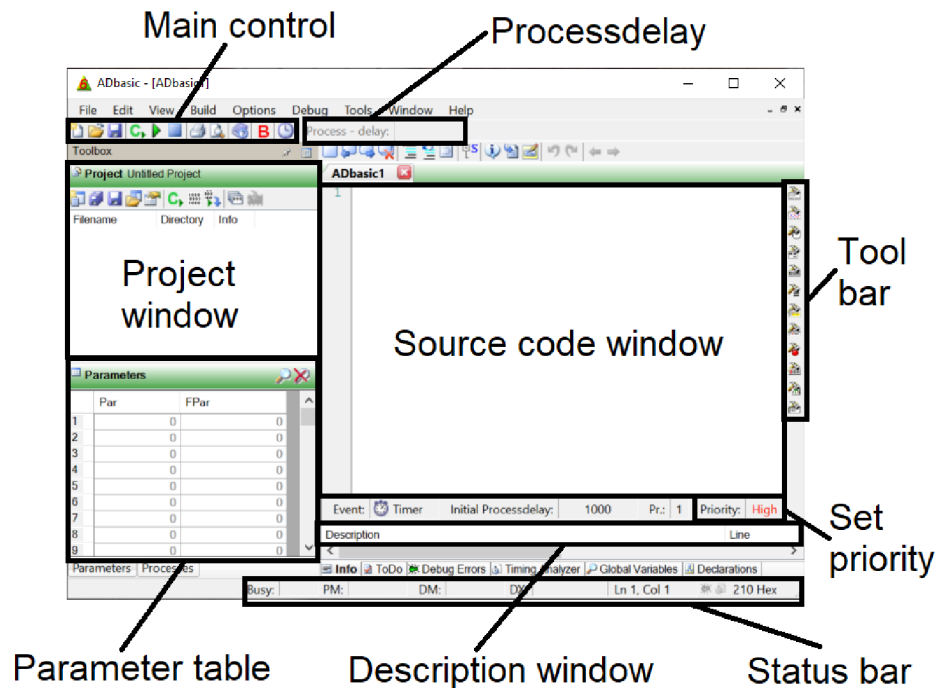e of the code is numbered. This feature is useful when a code error occurs, the error line displays in the description window [7].

If it is necessary to create multiple source codes that are dependent on each other, it is possible to create an ADbasic project. All the scripts from the project appear in the project window. Above the description window is the priority bar, where it is possible to see the set priority of the written code. There are two options of priority: high or low. When the high priority is set, the process has a preferential treatment from the operating system. This process cannot be interrupted and is always completed. The project window also display process delay and priority of each project script [7].

The processdelay is the feature of the code entered directly in the source code. This feature is set to delay the execution of individual processing. Together with the access time of the ADwin processor information, it is possible to set to execution speed of a single code process [7].

The parameter table monitors the parameters that have been defined in the source code. When measuring or controlling the system by means of the ADwin device, it is possible to monitor the change of parameters in real time via this table. The Par column is intended for the defined parameter that have been set as data type long. The Fpar column is intended for the parameters with float data type [7].

The main control element of the ADbasic development environment is the main control bar, which is shown in the *Figure 24*.
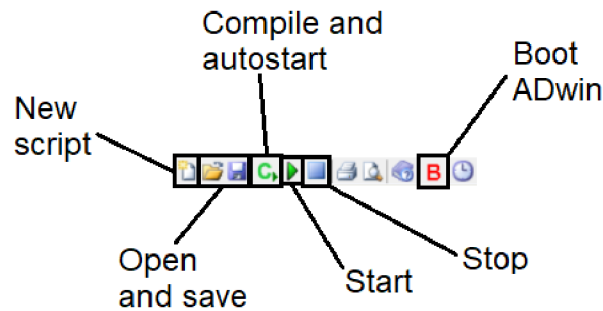
Figure 24 ADbasic main control bar

The New script icon is used to create the new script, which opens a new blank source code window. Next to this icon, there are icons for saving and opening an already created script or project. In order for the ADbasic development environment to connect to the ADwin device, the device must be booted into the ADbasic. For this option, there is an ADwin boot icon in the main control panel. Once the device is booted in ADbasic, the written code can be compiled and started with the Compile and autostart icon. Compile converts written code in the development environment to the into a form that is executable on the ADwin device. The running code can be stopped and started again by means of the Stop and Start icons [7].

6.3 ADwin-Gold-USB/-ENET

The Jäger company manufactures several models of real-time data processing devices. One of them is the ADwinGoldUSB/ENET. The USB or ENET in name determines the design of the device. The option is either USB connection to the PC or Ethernet connection to the PC[6].

Figure 25 ADwin-Gold-USB [6]

One of the features of this model is its small size that makes this device portable. The device's electrical installations are placed inside an aluminium encloser, which protects the components against external influence.

There are plugs for analog and digital inputs/outputs on the front panel of the device. There is also a PC connector and power supply control area on the panel. The power supply control area contains of power supply connector, power switch and LED. The LED indicates the on/off state of the device. The LED also indicates the device state:

- o Red light: Device is switched on, but it is not booted to the ADbasic.
- o Green light: Device is booted to the ADbasic.
- o Flashing green light: Device is booted into the ADbasic and the programmed code is compiled and started [6].

The ADwin-Gold is powered with 12 V via the power supply connector. Thanks to this low voltage supply, it is possible to use this device with an external power supply, which contributes to the feature of portability. The power supply can be interrupted on the front panel of the device by means of the power switch. The front panel of the ADwin-Gold-USB model is shown in the *Figure 26* [6].
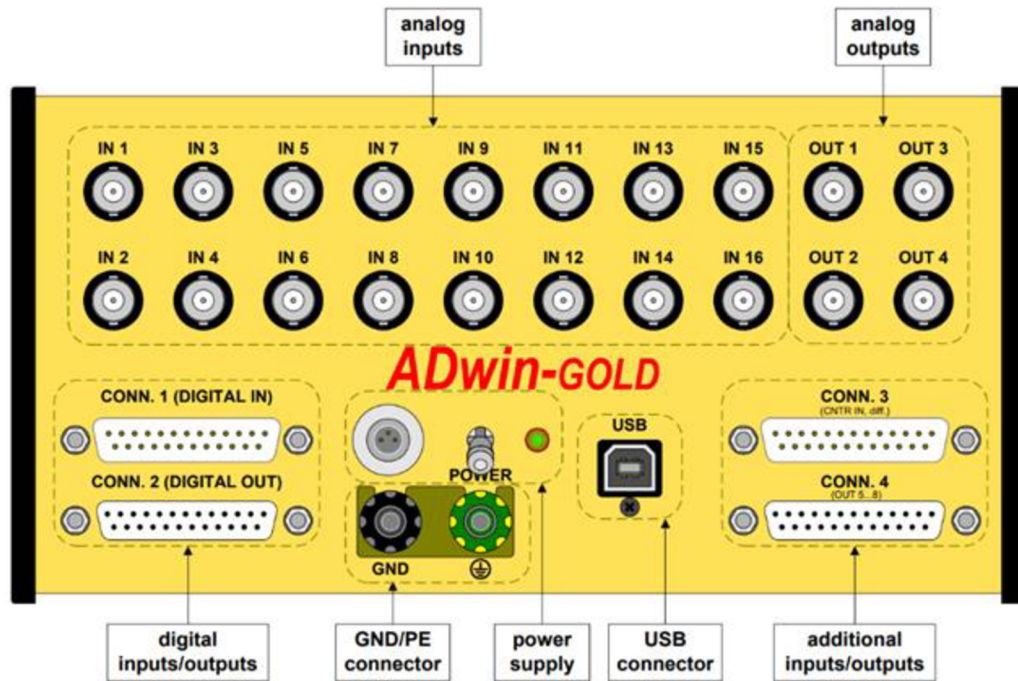
Figure 26 ADwin-Gold-USB front panel illustration [6]

6.3.1 PROCESSOR AND MEMORY

The processor contained in ADwin-Gold-USB is a digital 32 bit signal processor T9 (SHARC-DSP 21063) with a floating point, integer processing and access time of 24 ns. The inputs and outputs, in order to get maximum access times, are memory-mapped in the external memory section of the DSP. The DPS uses an external memory of 16 MB to storage large among of data [6].

6.3.2 ANALOG INPUTS

The device has two multiplexers and to them are connected a 16 BNC plugs as analog inputs divided into two groups. The multiplexers are converted by a 14-bit analog-to-digital convertor, which is the faster option (0.5 µs) or 16-bit analog-to-digital convertor, which is the more accurate option (5 µs) [6].

6.3.3 ANALOG OUTPUTS

There are two analog outputs with -10 V to 10 V range and 16-bit resolution [6].

6.3.4 DIGITAL INPUTS AND OUTPUTS

The system is equipped with two 25-pin D-Sub connectors. The connectors have 32 digital inputs or outputs. These connectors are programmable as an inputs or outputs [6].

6.3.5 CONNECTION

Depending on version, the system can be connected to computer via the USB or Ethernet interface. The connection of the electrical installation of the ADwin-Gold can be seen in more detail in *Figure 27* [6].
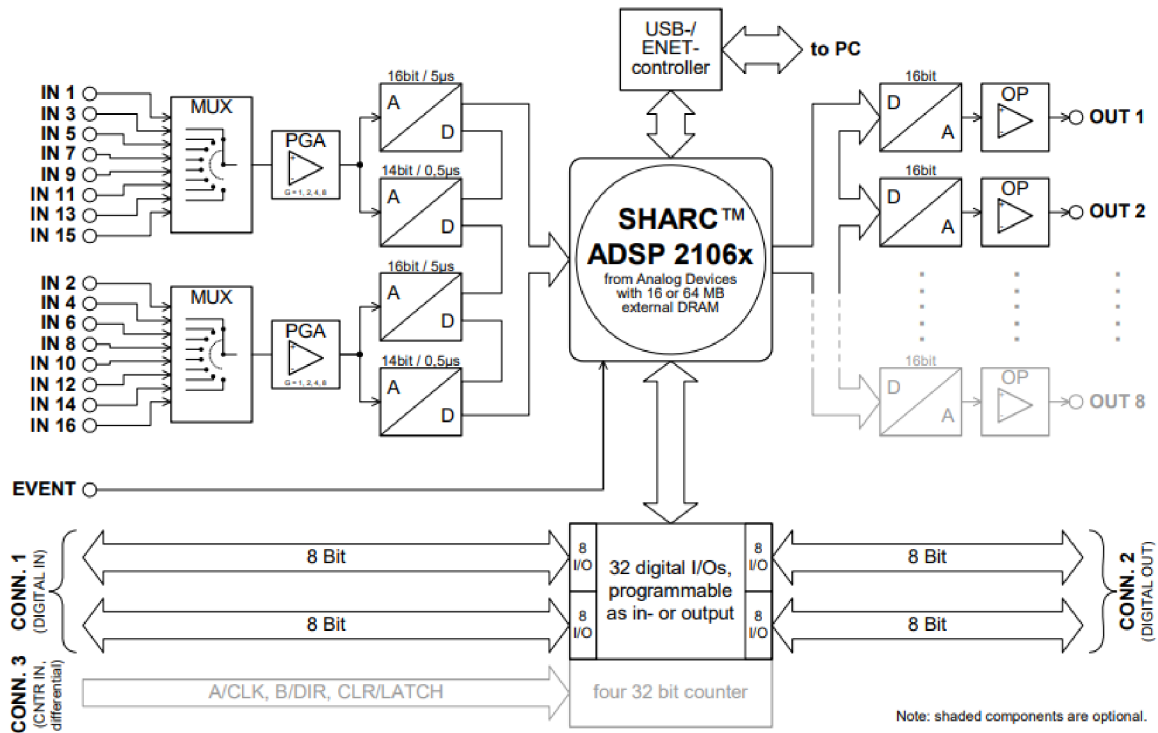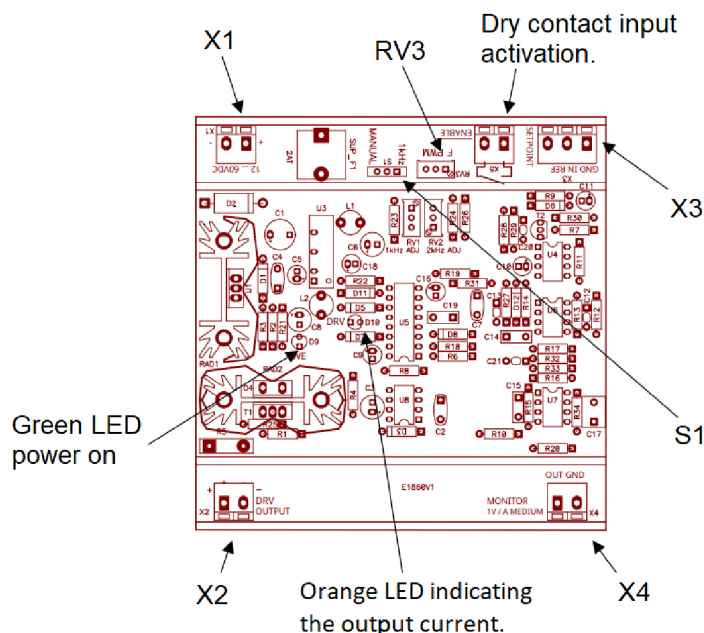

Figure 27 Block diagram of the ADwin-Gold [6]

7 **EFS1860V1** MODULE

Based on the given setpoint, the EFS1860V1 module is used to precisely regulate the mean value of the supply current. For a better understanding, the module is described according to the *Figure 28* [8].

Figure 28 EFS180V1 module main parts description [8]

The connection X3 sets the setpoint of the current mean value by the voltage signal in the range of 0 V to 5 V. The sensitivity of the module regulation corresponds to 1 V / A. Due to the defined duty cycle range for the PCV, current regulation is in the range from 50 mA to 5 A. The regulation of the current is performed in the module by means of the PWM signal. The PWM signal of the EFS1860V1 can be set on fixed frequency of 1 kHz (S1 connection) or it can be manually changed in range of 200 Hz - 2000 Hz (RV3 connection). The output connection X2 is used as a direct supply of the regulated current to the actuator (PCV). To check the value of the regulated current, it is possible to connect the oscilloscope via the X4 connection. The external power supply of 12 - 60 V DC to the EFS1860V1 is connected by means of X1 connector [8].
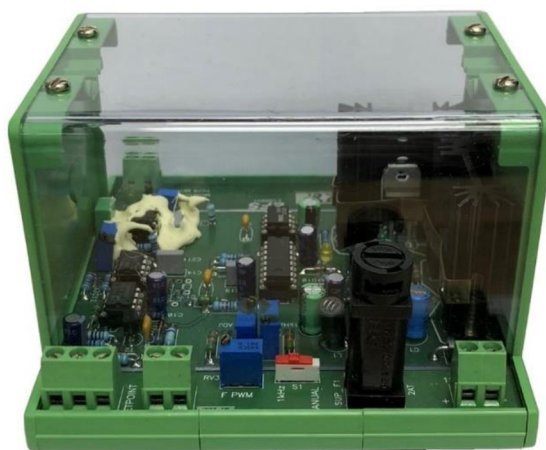
Figure 29 EFS180V1

8 COMPARISON OF LAYOUTS

In order to verify the correct function of the ADlayout, new tests were performed. These tests were also performed on the original test bench layout, in order to compare the speed of the current control. There was measured only the speed of current control in these tests. Therefore, it was not necessary to mount the PCV on the test rail and expose the PCV to the pressure. Thus, the PCV was connected only to the current supply.

There was performed two comparison tests to compare differences in speed of the current control. This comparison should provide information about the original test bench layout improvement by using the external ADlayout.

8.1 FIRST LAYOUT COMPARISON TEST

There was performed several jump changes to provide the visual comparison of both execution in the first test. Test was performed according to these boundary conditions:

- o Number of cycles: 6
- o Current low: 0 mA
- o Current high: 1800 mA
- o Current hold time: 2 sec

By means of an oscilloscope from the DEWEsoft company, the test data from both layouts were recorded. The recorded data were processed using the MatLab software. Both I/t dependences from the processed data were plotted together for better visual comparison (*Figure 30*).
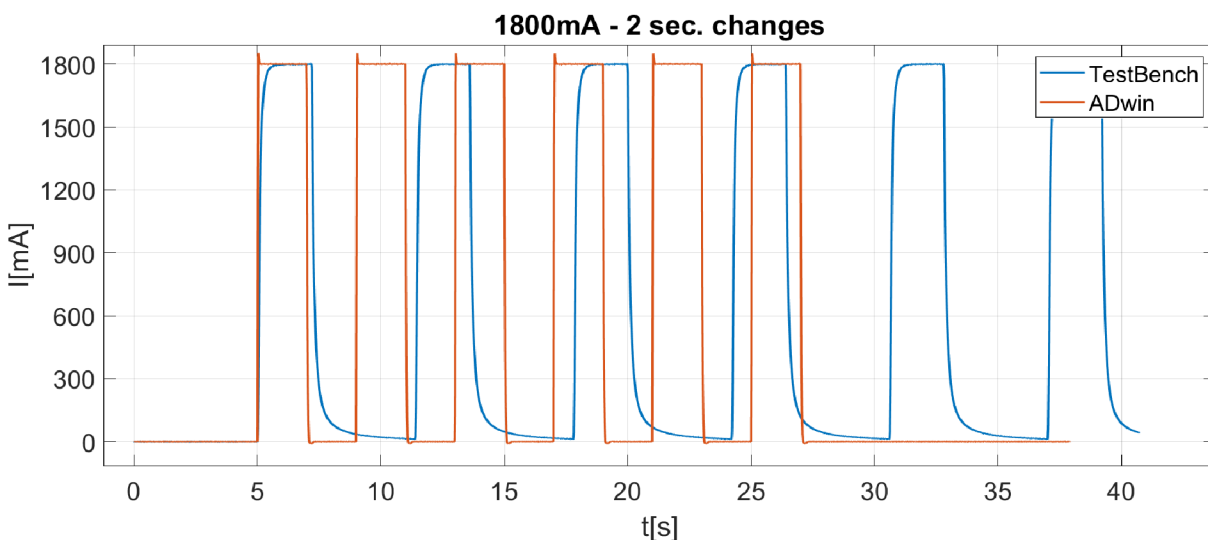
Figure 30 First layout comparison test plot

The comparison of the results shows a large difference in the total execution speed of the required 6 jump changes. The test bench layout shows a significant delay in the step-down change. For this reason, the zero current hold time is extended. This reason and the impossibility of entering the smaller value than 0.1 s in the development environment causes an increase of the total execution time of the test bench layout.

8.2 SECOND LAYOUT COMPARISON TEST

The performance of the second layout comparison test was due to illustrate these time differences numerically. The second test was executed on each layout 4 times to verify the measurement result. Test was performed according to these boundary conditions:

- o Number of cycles: 1
- o Current low: 0 mA
- o Current high: 1800 mA
- o Current hold time: 5 sec

From all the executed tests, the data of the current progress in time were recorded by means of the oscilloscope and processed using the MatLab software. From the processed data, the time interval of the step-up change (time from 0 mA to 1800 mA) and step-down change (time from 1800 mA to 0 mA) was determined. These time intervals were written down into the *Table 1* and their values were averaged.
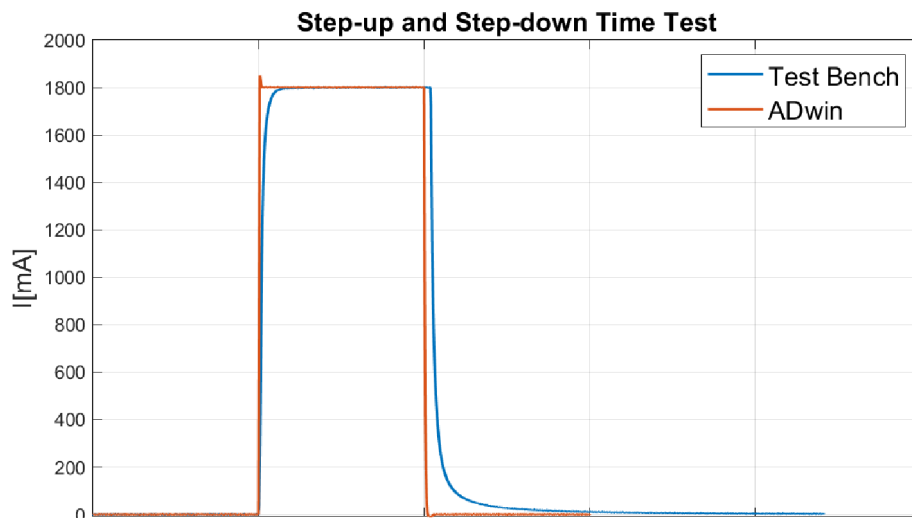
Figure 31 Second layout comparison test plot

Table 1 Step-up and Step-down timetable

1800 mA				
-	ADlayout		Test bench layout	
n.mess.	Up [s]	Down [s]	Up [s]	Down [s]
1.	0.031	0.102	1.025	17.369
2.	0.031	0.102	0.913	17.489
3.	0.031	0.102	0.909	17.938
4.	0.031	0.102	0.905	16.934
Mean:	0.031	0.102	0.938	17.433

From the mean values of the time intervals, the value of step-up change difference of 0.907 s was calculated. The time difference of the step-down change was calculated to be 17.331 s. From these results, when using the ADlayout, there is a significant improve in the current control speed. From the results is also clear that the ADlayout is more consistent when executing the jump changes.

9 TRIAL TEST

To verify the correct function of the ADlayout, it is necessary to perform a test that will simulate the real operating conditions of the PCV. Thus, a test that will generate dynamic changes (opening and closing) and verify the ADlayout's ability to control the current supply to the PCV. The test should also verify the closed-loop control function of the ADwin. That means the function to respond in real time to the feedback from the test bench.

The standard tests are performed before and after trial test to obtain pre-test and post-test information about the PCV condition. To avoid any mistake in the standard testing of the PCV, both tests were executed under the supervision of professionally trained test bench operator. The outputs of standard testing are two p/I characteristics on which it is possible to observe how the functionality of the PCV has change.

9.1 CONTACT FATIGUE TEST

The Contact fatigue test (CFT), which is an endurance test, was chosen as a suitable test that meets all the mentioned requirements. With the CFT, it is possible to generate the surface failure of the components if a sufficient number of load cycles is set. Due to the surface failure, it is then possible to verify the correct function of the durability test by means of analysis. The correct function of the test will confirm the function of the newly designed ADlayout [2].

9.1.1 CONTACT FATIGUE

Contact fatigue is one of the types of surface failures that occurs in metallic alloys. Many mechanical components are exposed to this type of surface failure. For example, valves, gears and bearings [9].

Unlike other material fatigue such as structural fatigue (bending and torsional), contact fatigue is the result of exposing the surface to alternating Hertzian stresses. The Hertzian type of stress is developed on the contact of two curved surfaces that are under the normal load. For this type of contact, a parabolic pressure distribution (p_0) from the normal load is assumed. The maximum shear stress distribution under the surface of the contact is shown in the *Figure 32*. According to this distribution, the maximum value of the shear stress is located at a certain depth below the surface [9].
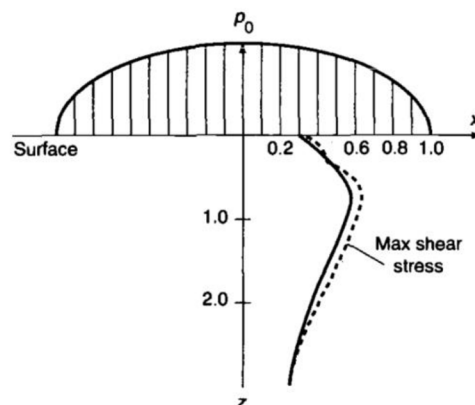
Figure 32 Parabolic pressure and maximum shear stress distribution:
x-Width of contact; z -Distance from surface; p_0-Pressure [9]

Thus, the alternating normal load generates the alternating shear stress below the contact surface. Alternating stress builds up the plastic strain below the surface. As the number of load cycles increases, a crack is initiated. The propagation of the cracks creates spalls (*Figure 33*), which are a typical surface failure during the contact fatigue [9].
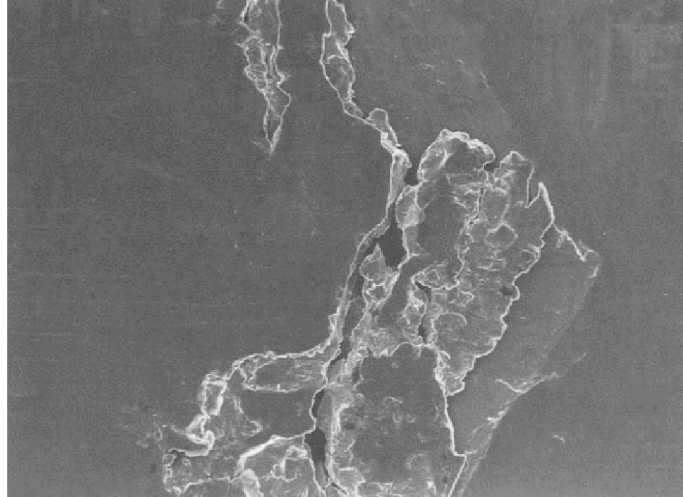
Figure 33 SEM of a fatigue spall on a roller bearing after 630 000 cycles [9].

Surface failure depends on many other influences that contributes to the crack initialization below the surface. For example, the occurrence of a frictional forces would result in this mechanism in increasing the shear stress below the surface. Another influences are the non-metallic inclusions in steels and heat treating of the material [9].

9.1.2 CFT RESULT HYPOTHESIS

Surface defects that occur on the PCV components are wear and cavitation. Since the presence of cavitation is only at a higher flow rate than that used for CFT, cavitation is therefore irrelevant in this case. Expected wear cases occurring in PCV after the CFT are:

- o Surface deformation.
- o Contact fatigue [2].

The seat-ball-pin contact should by the case of surface deformation. This hypothesis is based on the dynamic PCV control that takes place in the CFT. When the valve is closed the ball is pushed into the seat and the pin indent. This dynamic pushing in this number of cycles can cause a deepening of the pin indent.

For the ball-pin contact, this is the contact of two curved surfaces that are loaded by the normal force (opening and closing). The normal load is in CFT repeated in the large number of cycles. According to the mechanism explained in the chapter 9.1.1, contact fatigue should occur in ball-pin contact.

The Bosch company internal database contains a record of the ball movement during the PCV operation. From the record is possible to observe an axial movement of the ball (opening and closing) and a ball spin in some cases. This would mean, that a frictional force is also present in the ball-pin contact. This information should support the hypothesis about the contact fatigue occurrence in the ball-pin contact.
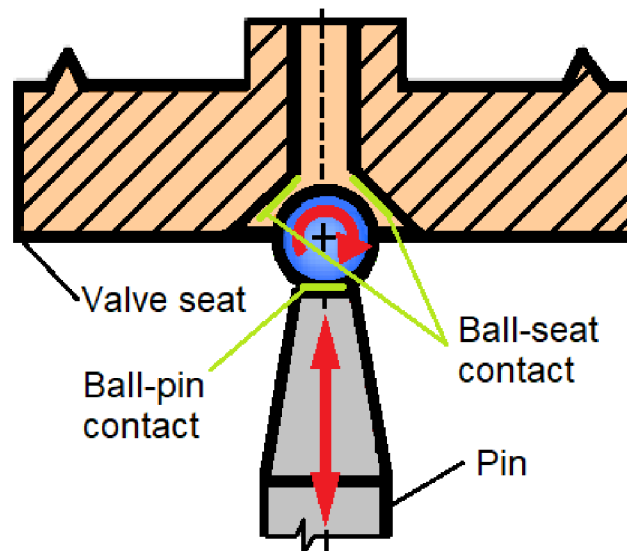

Figure 34 Ball movements

9.1.3 CFT LOGIC

The CFT contains fast-repeating cycle that simulate dynamic control of the PCV that occur during the real vehicle operation. There is a rail pressure regulation actuated by the PCV in this fast-repeating cycle. The CFT is governed by following boundary conditions:

- o Cycle duration time: 0.8 sec
- o Number of cycles: 300 000
- o Current low: 0 A
- o Current high: I_{max} [A]
- o Limit pressure: p_{max} [bar]
- o High-pressure pump speed: n [rpm]

The PCV is in two operating states during the cycle (fully open and fully closed), which depend on the rail pressure value. At the beginning of each cycle, the current supply to the PCV is set to the current high value. This means that the valve is in the fully closed state and the rail pressure is increased by the high-pressure pump. If the valve is in fully open state, the rail pressure has reached the limit pressure value or the time limit for one cycle has been exceeded. When one of these conditions occurs, the current supply to the PCV is set to the current low value and the pressure is released from the rail by opening the valve. After the execution of all set cycles, the CFT test is completed.

Based on the description of the CFT function, a block diagram (*Figure 35*) is created. According to the logic of diagram, a source code is programmed.
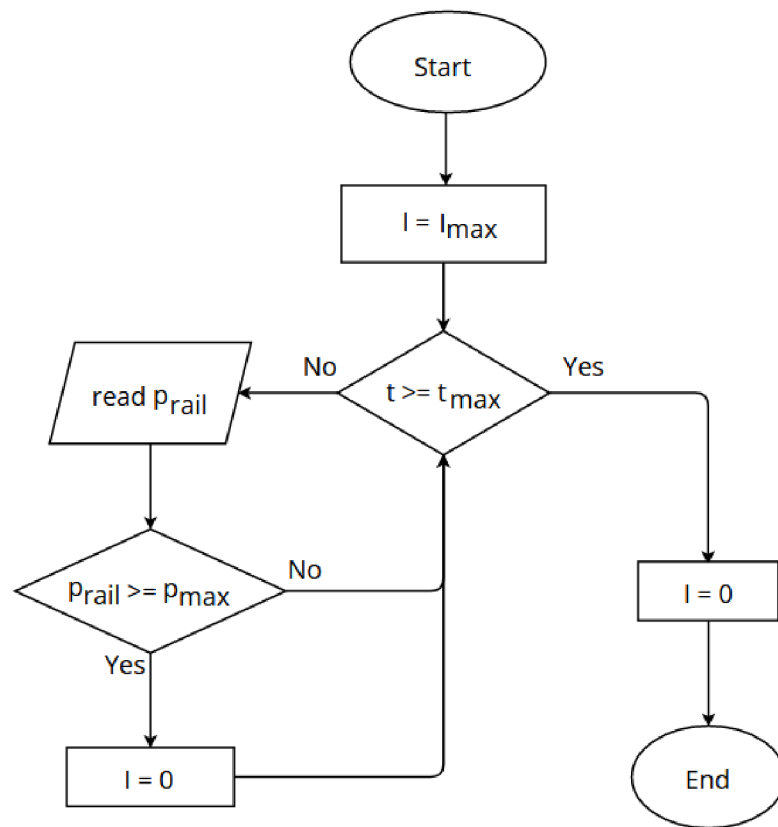
Figure 35 CFT block diagram

9.1.4 CFT PROGRAMING

Based on the logic of the CFT block diagram, a ADbasic project is programmed in the ADbasic development environment. The project consists of two scripts.

- o Pressure monitoring script
- o CFT logic script

The first script continuously monitors the value of the test rail pressure from the test bench pressure sensor. This pressure value is processed and provided to the second script. This rail pressure is read by second script and its value is compared to the set limit pressure. Second script contains the logic according to which the ADwin can modify the setpoint to the EFS module. The CFT logic script adjusts the setpoint value (current high, current low) in the **event** part of the script based on the received and processed data (pressure, time).

Before the setpoint adjustment logic is programmed in the script, the data types of used variables must be defined. The ADbasic command to define the data type is in the form of **dim** *variable* **as** *data type*. It must also be defined under which parameter number (**Par_number** or **Fpar_number**) the used parameters will be represented. The ADbasic command to define the parameter number is in the form of **#define** *parameter* **Par_number** [7].
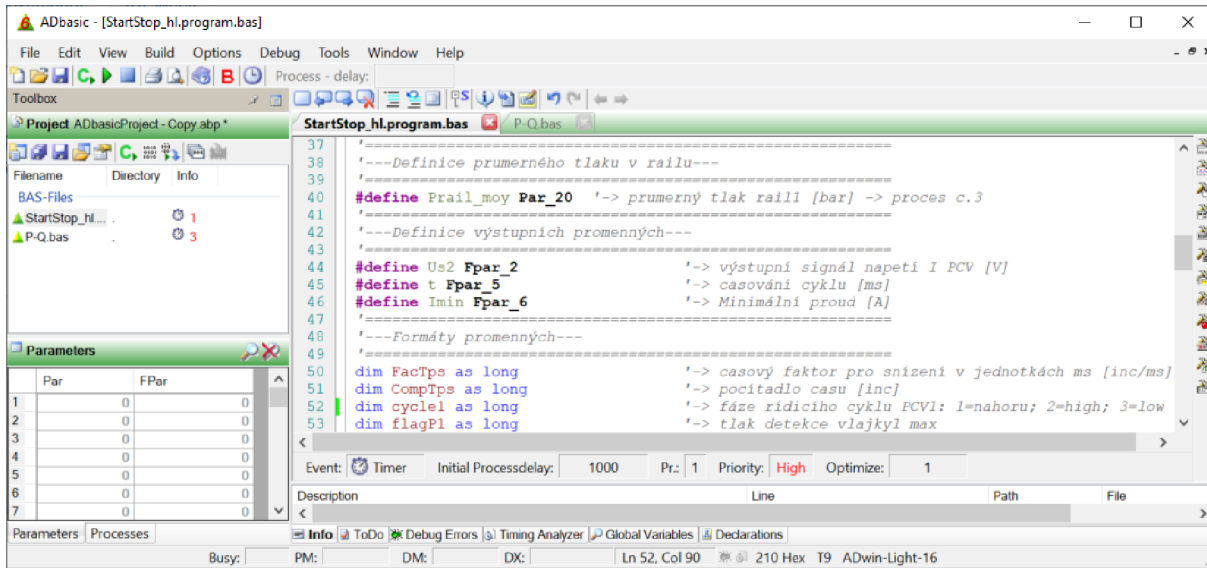
Figure 36 ADbasic develop enviroment

In order to control scripts based on the time values, a counter had to be programmed in the scripts (**lowinit:**). The function of the counter depends on the processor in the ADwin device and setting a **Processdelay**. The ADwin gold contains a T9 processor, which has access time of 25 ns [7]. There is set **Processdelay** to 20000 in the script. The processing time interval is calculated based on these settings to the 0,5 ms (*Equation (1)*). This means that each process is called every 0,5 ms. The counter **CompTps** is set in the script. The **CompTps** is written in the script using the **inc()** function, which adds a value of 1 to **CompTps** after each process [7]. In order to work better with the counter, there is set time factor (**FacTps**) of 2 in the script. By dividing the **CompTps** by the **FacTps**, the time value of 1 ms is given every two processes. Due to this recalculation, there is the time variable **t** [ms] in the script, according to which the code is controlled.

$$t_{int} = Processdelay \cdot ATP \qquad\qquad [ns] \qquad (1)$$

$$t_{int} = 20000 \cdot 25$$

$$t_{int} = 500000 \text{ ns}$$

According to logic of the script, the value of the setpoint **Us** is set, which is sent from ADwin device to the EFS module. For better orientation in the script, the real values of the pressure, current and voltage are used in the code. The setpoint **Us** corresponds to the value of the voltage signal, which controls the EFS regulation module. Since the DAC output operates with digital signal, which then converts to an analog signal, the **Us** setpoint must be converted to the digital signal (*Equation (2)*).

$$Us_{digital} = Us \cdot \frac{65536}{20} + 32768 \qquad\qquad [-] \qquad (2)$$

For the 16-bit output DAC is the digits range from 0 to 65536. This means that 0 V corresponds to 32768 digits, -10 V corresponds to 0 and 10 V corresponds to 65536 (*Figure 37*) [6]. The setpoint output is written in the code in form: **DAC(*number, value*)**. Where the *number* means the number of the output connector and *value* means the digital value of the setpoint **Us$_{digital}$**.
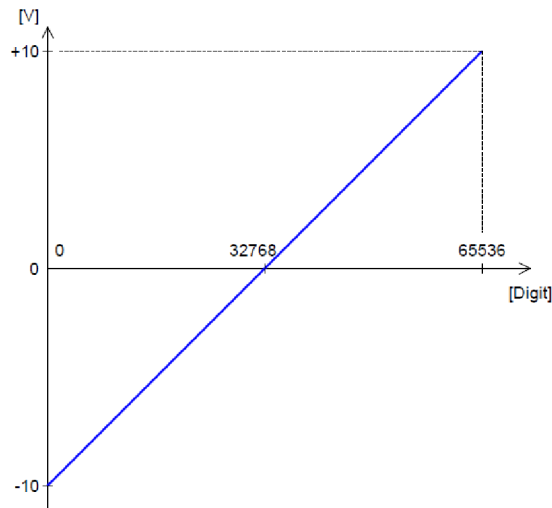

Figure 37 Zero offset in the standard setting of bipolar 10 Volt [6]

In the first script, the pressure value forms the pressure sensor is read. The analog voltage signal from the pressure sensor is transmitted to the ADwin device via the ADC input. At the ADC input, the analog voltage signal from the pressure sensor is converted to a digital signal. In order to work in the script with the pressure value and control the setpoint with it, the digital signal (**Urds$_{digital}$**) on the input must be recalculated back to the voltage signal (**Urds**) (*Equation (3)*). After recalculation, the voltage signal was according to the design of the pressure sensor recalculated to the pressure value. The pressure sensor from the HBM company has a signal conversion that 10 V corresponds to 3300 bars. Because of this conversion, the recalculated voltage signal Urds is multiplied by the value of 330. Thus, the value of the pressure in the test rail (**p$_{rail}$**) is obtained (*Equation (4)*).

$$\text{Urds} = \frac{(\text{Urds}_{\text{digital}} - 32768) \cdot 20}{65536} \qquad\qquad [V] \qquad\qquad (3)$$

$$P_{\text{rail}} = \text{Urds} \cdot 330 \qquad\qquad [bar] \qquad\qquad (4)$$

9.1.5 CFT EXECUTION

The trial test was performed on the currentless open PCV. The oscilloscope was used to obtain the test record. Using cables with BNC connectors, the oscilloscope was connected to the test bench signal output (pressure record) and to the EFS module (current record).

First, the PCV and the low-pressure drain were mounted on the test rail. Then the current supply from the EFS module was connected to the PCV. After the PCV has been correctly prepared, the test area was closed for the safety reason. Then in the LabVIEW control environment of the test bench, a constant speed of the high-pressure pump was set. By the flow of the fluid through the open PCV, the test bench hydraulics layout was heated to the

operating temperature. To accurately record data, the oscilloscope was calibrated before recording the CFT execution.
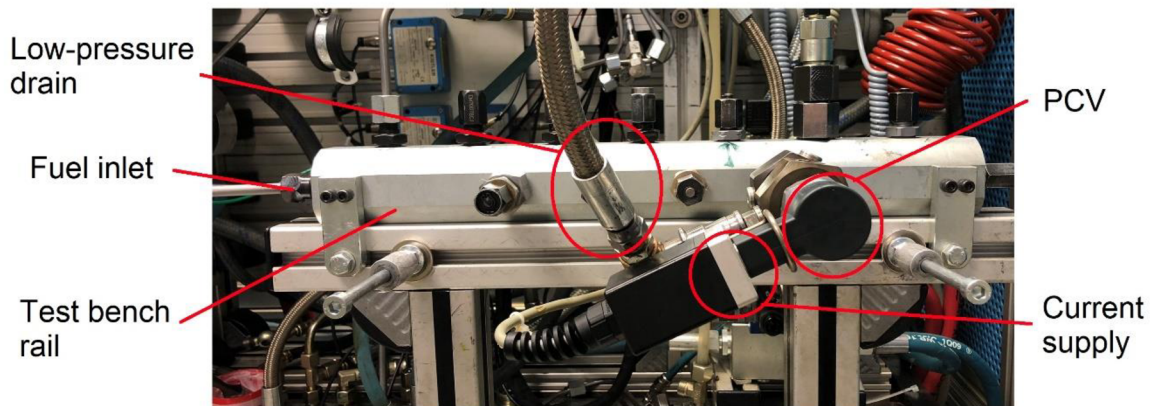

Figure 38 PCV mounted on the test bench rail

After calibrating the oscilloscope and heating the hydraulic layout, the programmed project was sent into the ADwin device from the PC. Before compiling and starting the programmed project, the oscilloscope data record was started.

After the first run of the CFT, the recorded data from the oscilloscope showed that the pressure regulation did not proceed as expected. The record showed that the rail pressure did not reach the limit pressure value in the 0,8 s cycle time range. Therefore, the regulation of supply current to the PCV is not performed as programmed in the code. The reason for this problem is that the speed of the high-pressure pump is set too low. At first, the speed of the high-pressure pump was set at 300 rpm (*Figure 39*).
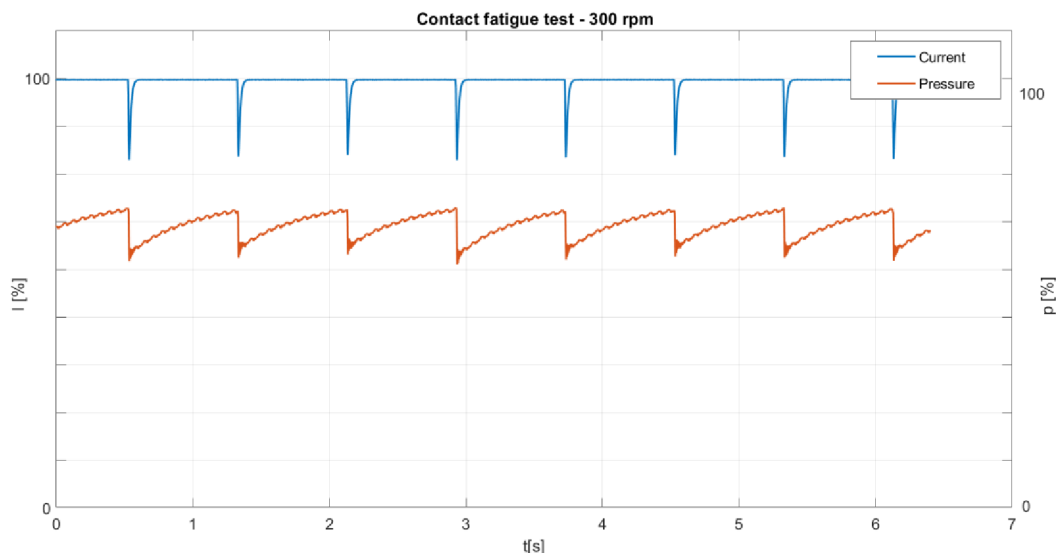

Figure 39 CFT plot: 300 rpm setup

To solve the problem of slow pressure rise, the speed of the high-pressure pump was increased to 900 rpm. The higher speed solved problem with the slow pressure rise, however the speed of the supplied current regulation was performed too quickly. Thus, the changes were not equally distributed in the cycle record (*Figure 40*).
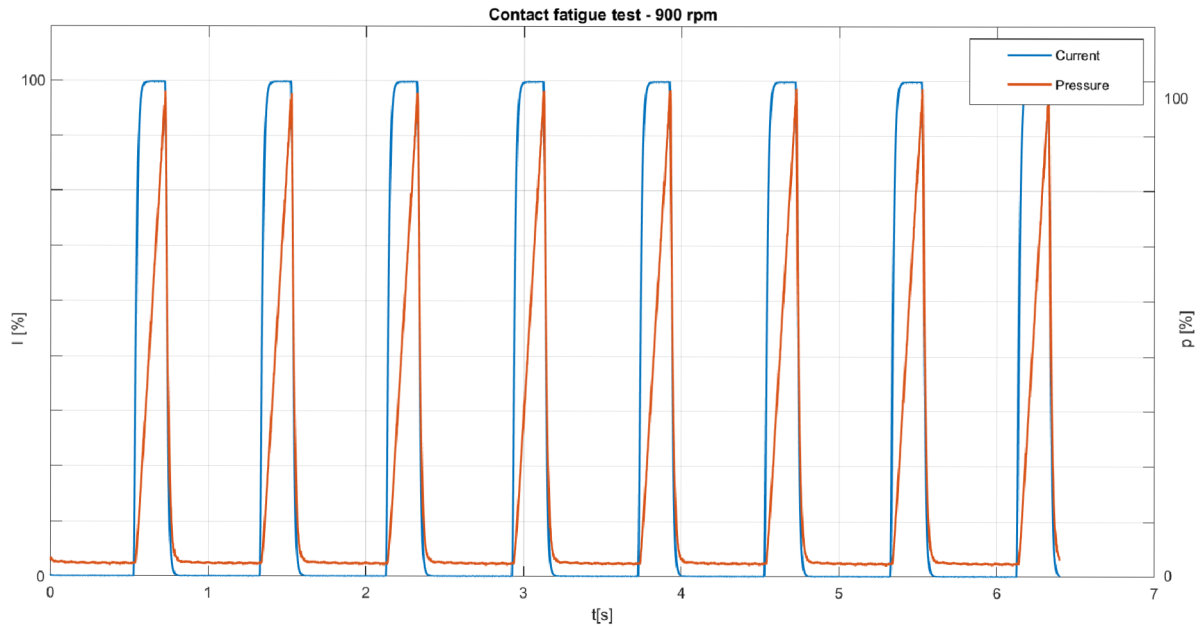
Figure 40 CFT plot: 900 rpm setup

As the ideal speed of the high-pressure pump that was used for the CFT is 600 rpm. At this pump speed, the pressure rise is fast enough, and the changes are more clearly distributed over the cycle record (*Figure 41*). During the test, the movements of the low-pressure hose were visible in the test area of the test bench. This confirms the occurrence of dynamic hydraulic changes in the system. Thus, dynamic opening and closing of the PCV. In total, the test ran for 66 hours and 40 minutes.

Figure 41 CFT plot: 600 rpm setup (final setup)

10 TEST RESULTS EVALUATION

The aim of the testing is to verify whether the product meets the expected functionality and quality parameters. The next step after testin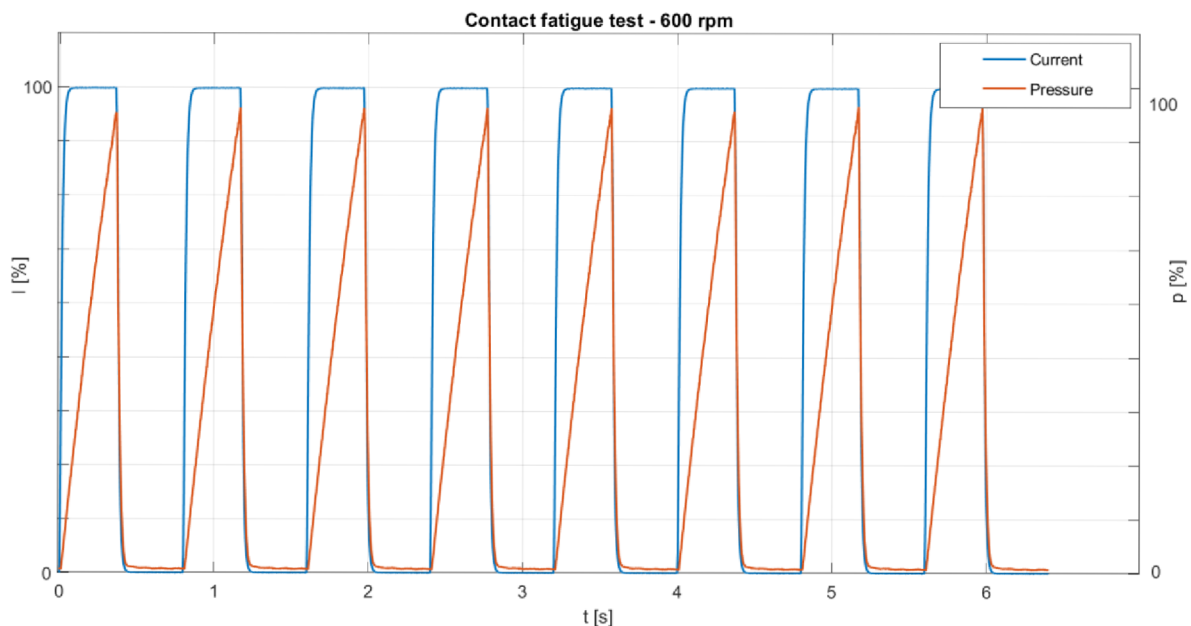g is to evaluate the results of the testing and analyse the tested product. In this case, these after testing processes can help verify the correct operation of the newly designed ADlayout and verify the surface failure hypothesis.

10.1 STANDARD TESTING RESULTS

As a first evaluation of the CFT, the result of both (pre-test, post-test) p/I characteristics were compared. After obtaining the results of both tests, for the better clarity, both p/I characteristic were inserted into one plot (*Figure 42*).



Figure 42 Comparison of p/I characteristics

There is a smooth pressure regulation visible in the p/I characteristic before the CFT. There is also shown that the observed working point is within the defined tolerance field. The same smooth regulation is visible in the p/I characteristic after CFT, but the post-test characteristic is not within the tolerance field.

There is also visible difference between both p/I characteristic in the current requirement to maintain the required system pressure. After testing, the PCV requires less current to maintain the required system pressure than was required for the PCV before testing. This phenomenon is caused by pushing ball deeper into the pin indent. The depth increase is the result of the large number of test cycles and dynamic opening and closing of the PCV. The deeper indent causes the reduction of the WAG. For this reason, the after-test p/I characteristic moved toward the lower values of the current. A more detailed explanation of this phenomenon can be found in the chapter 2.3.

10.2 VISUAL ANALYSIS

The PCV had to be disassembled into the individual parts in order to obtain the visual post-test results. Standardly, this process would involve taking photos of all PCV components and examining the taken photos. In this case, it is an investigation following the CFT, so the main inspected component is the PCV pin. According to experience, the other components are less damaged than the PCV pin. After disassembly, the PCV pin was cleaned and prepared for investigative photography.

Investigation photos were taken by means of Keyence digital microscope, which is used for its large depth of field. For the comparison, photo of the new untested PCV pin was also taken. These images were placed side by side for easier comparison of differences (*Figure 43*).
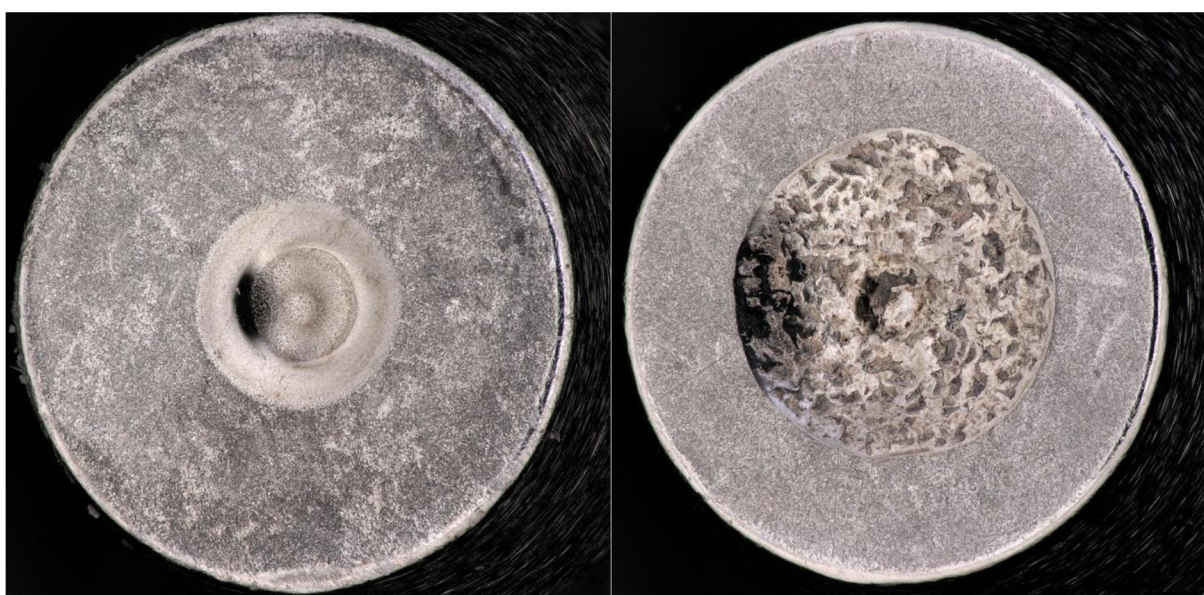
Figure 43 Pin front face: indent comparison - Untested pin (left); Post-test pin (right)

There is a photo of the tip of the pin on the *Figure 43*, where the increase of the diameter of the pin indent is obvious. Larger diameter of the pin indent proves that the ball is pressed deeper into the pin. On the post-test pin, the occurrence of the surface damage can be seen in the indent area of the pin.

For more detailed representation of the pin surface, photos of the post-test pin surface were taken by means of scanning electronic microscope (SEM), which were compared to the surface of the new untested pin.
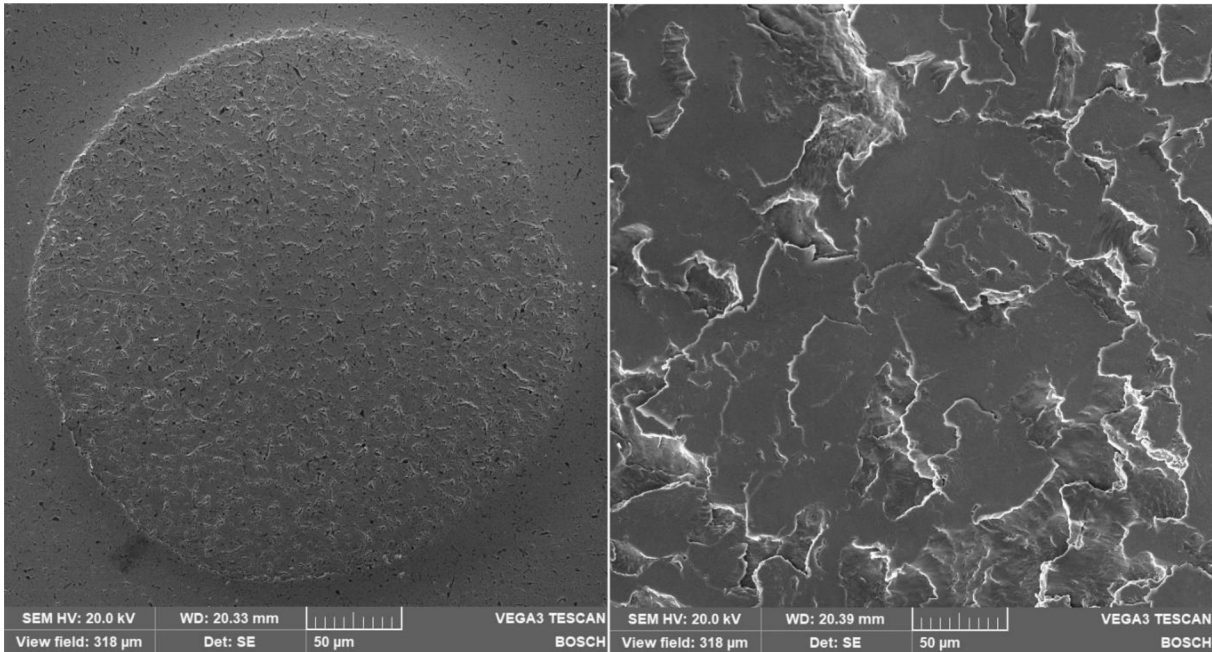
Figure 44 Pin indent: surface comparison – Untested pin (left); Post-test pin (right)

The electronic microscope images show a large difference in the surface structure of two pins. The occurrence of the spalls can be seen in the indent area of the post-test pin, which indicates the presence of the contact fatigue. There is possible to see the smooth indent surface of the new untested pin in the 318 μm image field of view in in *Figure 44*. Due to the enormous surface damage appearance, only the spalls are visible under the same field of view on the surface of the post-test pin. *Figure 45* shows the transition between loaded and unloaded area of the front face of the post-test pin.

Figure 45 Pin front face: unloaded and loaded surface transition

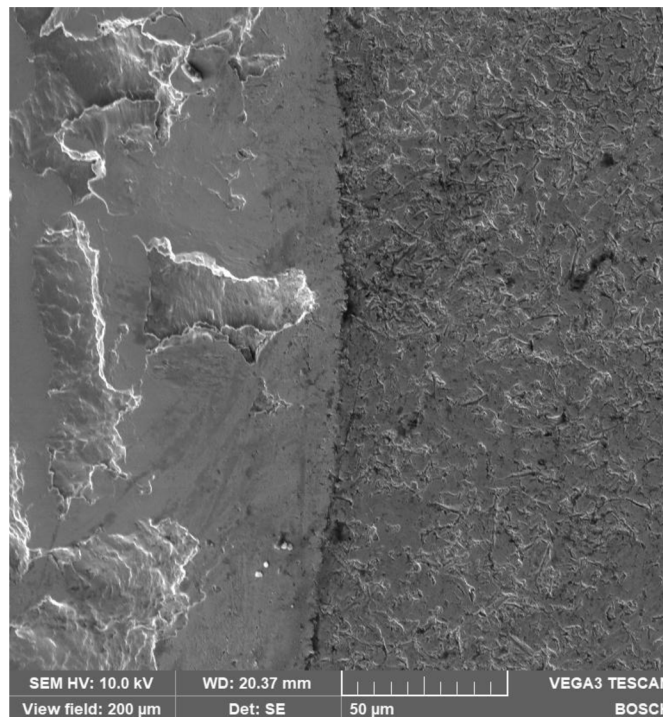## 10.3 METALLOGRAPHIC ANALYSIS

In this case, the metallographic analysis is performed to examine the subsurface of the ball-pin contact. In the subsurface, according to the hypothesis mentioned in chapter 9.1.2, the cracks should be found. These cracks should initialize the spalls occurrence that have been revealed by visual analysis in chapter 10.2.

Metallography is the science discipline of observing the microstructure of all type of metallic alloys. From the data provided by means of metallographic analysis, it is possible to determine the reliability of the products or to learn why a material failure has occurred. Before performing the metallographic analysis, it is necessary to prepare the component into a form in which can be examine. This preparation has clearly given procedure, which is important to follow for success of the analysis. Prepared specimen is then analysed by means of the metallographic microscope [12].

10.3.1 SPECIMEN PREPARATION

The target object of this analysis is the indent of the PCV pin. Due to the size of the pin, the pin is cut in half to fit into the hot mounting press. Using the hot mounting press, the cut pin is mounted in a resin. In order to observe the microstructure of the contact subsurface, the cut pin is grinded to the centre of its diameter. Furthermore, the specimen is finally grinded and polished. At the end of the preparation process is the specimen etched for the better visibility of the microstructure [12].

Figure 46 Prepared specimen mounted in resin

10.3.2 ANALYSIS EXECUTION

The expected size of the subsurface cracks is in the range of micro millimetres. Therefore, the images of the indent subsurface are taken by means of metallographic microscope. Photos of the subsurface cracks were taken before the etching process (*Figure 47* and *Figure 48*). The reason for taking the photos before the etching process is the greater visual contrast between the crack and material. Thus, it is easier to detect the cracks.

After etching the specimen, the same photos were taken in which the microstructure of the material can be seen. The *Figure 49* therefore serves as more realistic representation of the cracks below the contact surface.
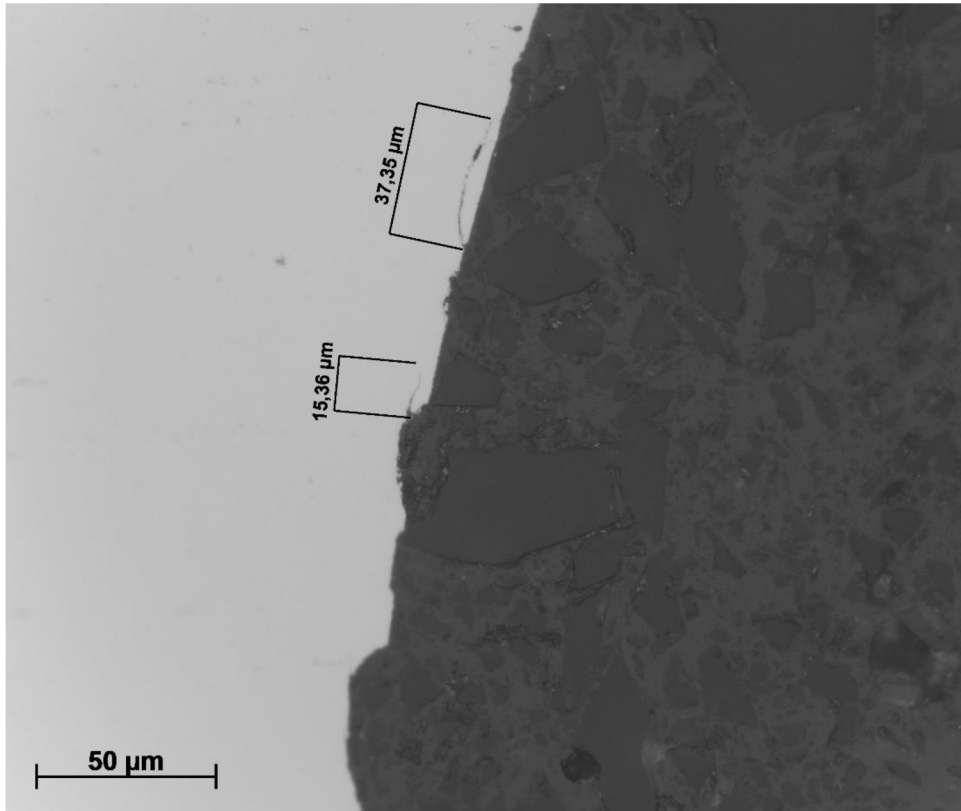
Figure 47 Subsurface cracks of the pin indent (500x)
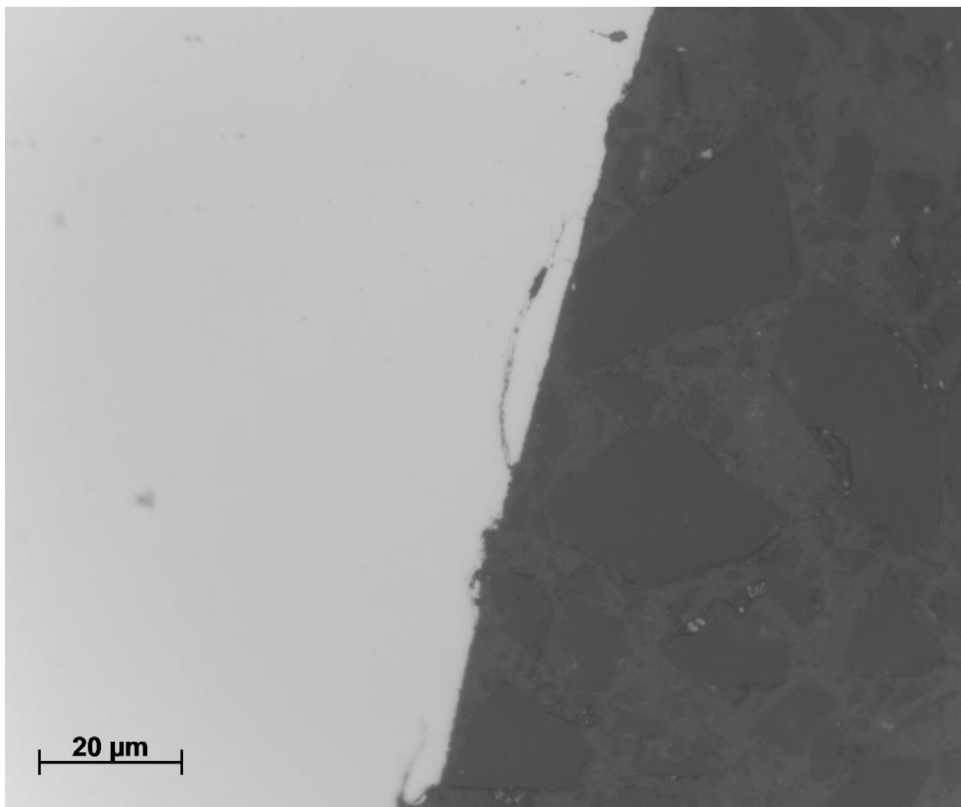
Figure 48 Subsurface cracks of the pin indent (1000x)
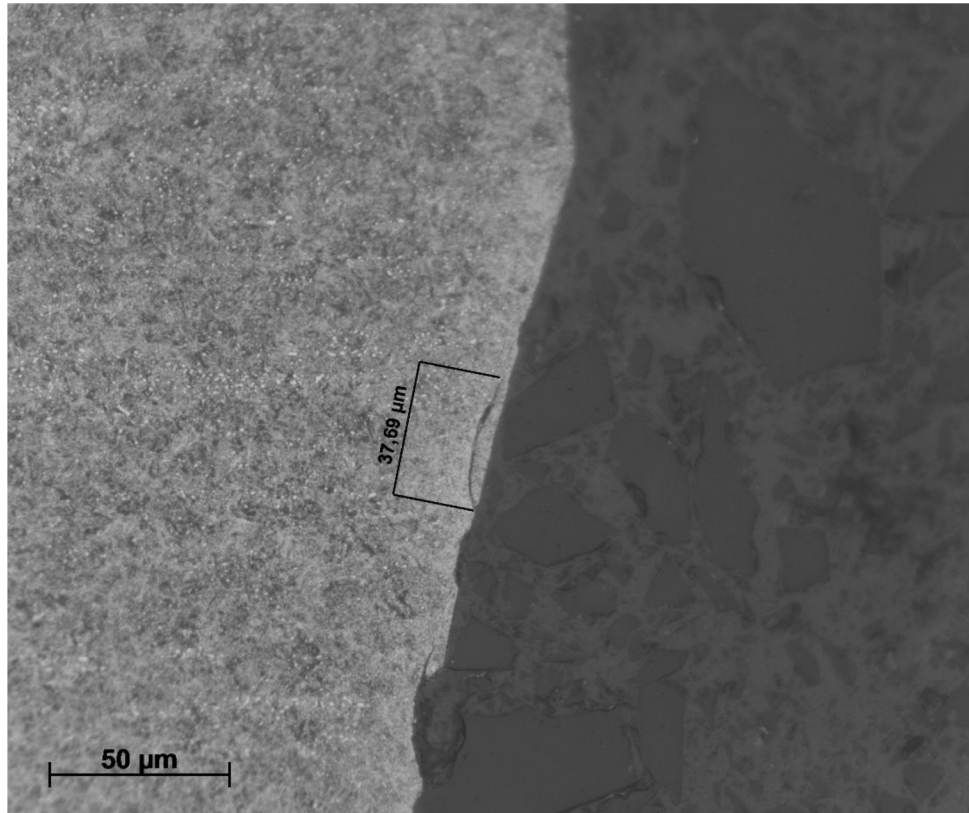
Figure 49 Subsurface cracks and microstructure of the pin material (500x)

Two cracks can be found in the subsurface photos. The largest crack found under the contact surface is 37.69 µm long. The *Figure 48* shows in more detail the development of the crack before it separates from the indent surface.

From these subsurface figures it is possible to confirm the subsurface cracks occurrence. Thus, it can be confirmed that there is an actual presence of the contact fatigue on the pin indent after the CFT execution. Verification of all functions of the newly designed ADlayout is therefore completed and the ADlayout is now ready for use.

CONCLUSION

The aim of this diploma thesis was focused on processing information about the function of the original test bench layout and testing methods of the pressure control valve (PCV). Based on this obtained information, then correctly implement ADwin into the development test bench and thus expand the use of the test bench for PCV testing.

From the information provided by Bosch and the specialised literature, knowledge regarding the operation of the PCV was obtained. From these sources it was found that during the real operation of the PCV, the current supply to the coil is regulated by means of a PWM signal. This method of current control had to be researched in more detail, in order to use it correctly in the new layout design. Furthermore, the diploma thesis dealt with the understanding of the ADwin device and the way in which it can be programmed. For this part of the diploma thesis, it was necessary to learn to control the ADbasic development environment of the ADwin system and learn the syntax of its programming language.

The tests performed on the original test bench layout revealed a shortcoming in the area of current control. This shortcoming concerned the control speed of the current jump change. The control speed is slower than required in some special PCV testing methods due to the testbench setup. Based on the information received from previous chapters, this problem was solved by designing and implementing an additional circuit. This circuit bypasses the test bench current control layout and replaces it with the ADwin control.

This new layout (ADlayout) was compared to the original layout of the test bench. Visual and numerical results were obtained from this comparison. The visual result showed that the shape of the current change performed by ADlayout corresponds more closely to the desired shape than the current change shape performed by original layout. The numerical result provided us with the time differences values of the step change between the current-low and current-high values. The time difference of the jump change between the individual layouts is 0.907 s for the change from low to high in favour of ADlayout. The difference of the change from high to low is 17.332 s also to the favour of ADlayout. The visual and numerical results therefore showed a speed increase during the supply current control to the PCV.

The correct function of the of the ADlayout was verified by a Contact fatigue test (CFT). The CFT was programmed by means of ADbasic development environment for the ADwin device. According to the test bench pressure feedback, the ADwin device controlled dynamic changing of the current supply to the PCV. The test run for 66 hours and 44 minutes. Then the visual and metallographic analysis was performed to obtain the post test results. The obtained result from the analyses was the contact fatigue occurrence on the surface of the PCV pin indent. This result confirmed the hypothesis described in chapter 9.1.2, which is focused on the assumption of the PCV components condition after the CFT. The performed test therefore checked the functionality of the newly implemented circuit in the test bench.

The result of this diploma thesis is the functional additional circuit for the test bench, which expands the possibilities of the original test bench layout. Thanks to the programmability of the ADwin device, it is possible to perform a large number of tests with various logical operations. The portability of the devices used in the additional circuit contributes to the possibility of implementing the circuit into the other testing devices.

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ABBREVIATIONS AND SYMBOLS

ADC	Analog-to-Digital converter
ATP	Access time of the processor
CFT	Contact fatigue test
CPU	Central processing unit
CRS	Common-rail system
DAC	Digital-to-Analog converter
DSP	Digital signal processor
ECU	Electronic control unit
EDC	Electronic diesel control
FPU	Floating-point unit
MeUn	Metering unit (Fuel metering valve)
PWM	Pulse-Width modulation
RPS	Rail pressure sensor
SEM	Scanning electronic microscope
WAG	Working air gap

CompTps	[-]	Script counter
Down	[s]	Step-down time interval
FacTps	[-]	Time factor
F_{Mag}	[N]	Magnetic force generated by spring
$F_{RailPressure}$	[N]	Force generated by rail pressure
F_{Spring}	[N]	Force generated by spring
I	[A]	Current
I_{max}	[A]	Maximal value of current
I_{max}	[A]	High value of the current
I_{min}	[A]	Minimal value of current
I_{nom}	[A]	Optimal value of current
n	[rpm]	Electric motor speed
p	[bar]	Pressure
p_{max}	[bar]	Rail pressure limit value
p_{rail}	[bar]	Rail pressure
Q	[l/h]	Flow rate
t	[s]	Time

t_{int}	[ms]	Time interval
t_{max}	[ms]	Cycle time limit / Cycle duration time
Up	[s]	Step-up time interval
$Urds$	[V]	Voltage signal value from the pressure sensor
$Urds_{digital}$	[-]	Digital value of the voltage signal value from the pressure sensor
Us	[V]	Voltage signal value of the pressure setpoint
$Us_{digital}$	[-]	Digital value of the voltage signal value of the pressure setpoint
ΔF_{high}	[N]	High sensitive magnetic force area
ΔF_{low}	[N]	Low sensitive magnetic force area
$\Delta F_{opt.}$	[N]	Optimal sensitive magnetic area
ΔWAG	[mm]	Pressure control range