

Stepless fault injection for electrohydraulic actuator

Erik Jönsson



LUND
UNIVERSITY

Department of Automatic Control

MSc Thesis
ISRN LUTFD2/TFRT--5983--SE
ISSN 0280-5316

Department of Automatic Control
Lund University
Box 118
SE-221 00 LUND
Sweden

© 2015 by Erik Jönsson. All rights reserved.
Printed in Sweden by Tryckeriet i E-huset
Lund 2015

Abstract

One of the cases for testing the BorgWarner GEN V clutch is to see if pump and motor malfunctions are detected by the software. Until now there have been a couple of fixed configurations testing clutches with different faults. The goal was to investigate if these configurations could be replaced by a normally functioning motor and pump connected to electrical circuits to mimic faulty clutches, which would ultimately lead to more flexibility during the testing. The work has been carried out at BorgWarner TTS in Landskrona.

Acknowledgements

Thanks to my supervisor Per Söderberg for help and feedback, and Jonas Jönsson for having me doing the thesis.

Contents

| | |
|--|----|
| 1. Introduction | 12 |
| 1.1 About BorgWarner | 12 |
| 1.2 The GEN V clutch | 12 |
| 1.3 Testing | 14 |
| 1.4 Problem formulation..... | 14 |
| 1.5 Outline of the report | 14 |
| 2. Background..... | 15 |
| 2.1 Hardware-in-the-loop testing..... | 15 |
| 2.2 The test rig..... | 16 |
| 2.3 The ECU interface | 18 |
| 2.4 Motor and pump | 20 |
| 3. Equipment..... | 21 |
| 4. Implementation | 22 |
| 4.1 Building the faulty pumps | 22 |
| 4.2 Measuring the characteristics | 22 |
| 4.3 Interpreting the measurement data | 24 |
| 4.4 Simulations | 26 |
| 4.5 Implementing a model for injection | 27 |
| 4.6 Building the electronics | 28 |
| 4.7 Adding the configuration to the VT System..... | 31 |
| 5. Results and discussion | 33 |

| | |
|---|----|
| 5.1 Measurements – old actuators | 33 |
| 5.2 Simulations | 36 |
| 5.3 The new injection module | 39 |
| 5.4 Comparison between the old and the new system | 43 |
| 6. Conclusion | 44 |
| Bibliography | 45 |

List of figures

- 1. Introduction 12
 - 1.1 About BorgWarner 12
 - 1.2 The GEN V clutch 12
 - 1.3 Testing 14
 - 1.4 Problem formulation 14
 - 1.5 Outline of the report 14
- 2. Background 15
 - 2.1 Hardware-in-the-loop testing 15
 - 2.2 The test rig 16
 - 2.3 The ECU interface 18
 - 2.4 Motor and pump 20
- 3. Equipment 21
- 4. Implementation 22
 - 4.1 Building the faulty pumps 22
 - 4.2 Measuring the characteristics 22
 - 4.3 Interpreting the measurement data 24
 - 4.4 Simulations 26
 - 4.5 Implementing a model for injection 27
 - 4.6 Building the electronics 28
 - 4.7 Adding the configuration to the VT System 31

| | |
|---|----|
| 5. Results and discussion | 33 |
| 5.1 Measurements – old actuators | 33 |
| 5.2 Simulations | 36 |
| 5.3 The new injection module | 39 |
| 5.4 Comparison between the old and the new system | 43 |
| 6. Conclusion | 44 |
| Bibliography | 45 |

Abbreviations

ECU – Electric Control Unit

DTC – Diagnostic Trouble Code

CAN – Controller Area Network

GEN V – Fifth generation clutch

PWM – Pulse Width Modulation

OA – Operational Amplifier

DUT – Device Under Test

HIL – Hardware in the loop

1. Introduction

1.1 About BorgWarner

BorgWarner Torque Transfer Systems (TTS) is a part of BorgWarner, which is an American company. The TTS department primarily develops and manufactures transfer cases, slip clutches and differentials.

1.2 The GEN V clutch

The BorgWarner GEN V clutch is used for enabling an extra pair of wheels when the primary driving wheel pair closest to the engine loses grip. Its placement in the vehicle is shown in Figure 1.1. The advantage over constant four-wheel drive is better gas mileage. The first generation of the clutch was patented in the 90s and

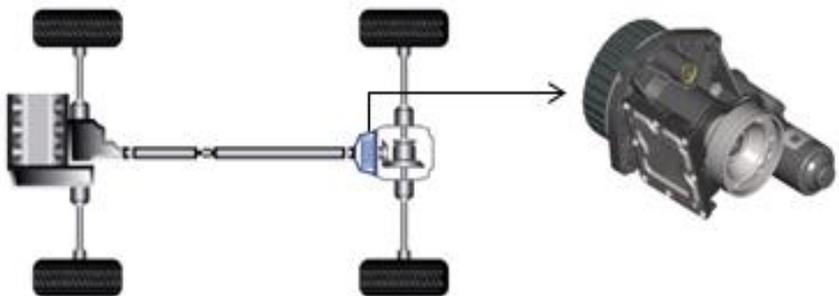


Figure 1.1. Placement of the clutch in the vehicle.

was a completely mechanical solution that was activated by the rotation speed difference between the front and rear wheel pairs. Today the activation works via the CAN-network, where the separate wheels speeds are available to the electric control unit (ECU). This means that the behavior of the clutch can be configured according to customer-specific needs.

When the speed of the driving wheels becomes higher than the non-driving wheels we have traction problems and the clutch should engage. Upon activation, lamella discs that are attached to the ingoing and outgoing axes are pressed together, thus transferring rotation between the axes. The force that presses the discs together works via a hydraulic pressure that is built up by a piston pump. The pump is driven by an electrical DC-motor, which in turn is controlled by a voltage that the ECU applies. Figure 1.2 shows the clutch cut in profile.

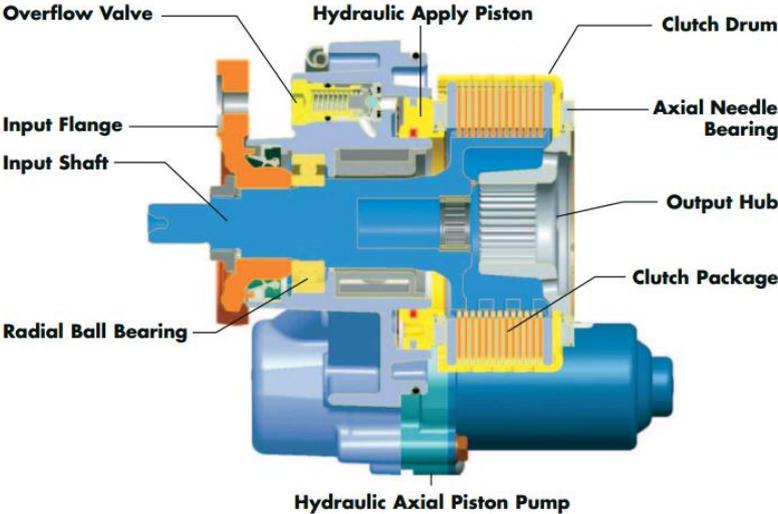


Figure 1.2. Clutch overview.

1.3 Testing

To make sure that the product shipped to the customer meets the requirements, the product must obviously be extensively tested, and the sooner faults can be detected the less money will be lost. Since this thesis was made at the software testing department of BorgWarner TTS, the focus will be on the software testing. The software testing can for instance involve response time, that a correct voltage is applied to the motor at the correct time, or that the ECU detects hardware faults and throws one or more diagnostic trouble codes (DTC), which are saved in the memory and can be read out by a service station or similar.

1.4 Problem formulation

To be able to test that the software detects faulty hardware, part of the test rig contains four fixed configurations with one normal and three faulty actuators. The goal of this work is to replace these configurations with a normally functioning actuator connected together with electrical circuits to imitate the voltage and current characteristics from the previous fixed faulty actuators and to steplessly inject any fault scenario in between. Disadvantages with the current solution is that only three fixed cases with faulty hardware can be tested and that it produces false voltage and current characteristics when switching from normal to faulty actuator to simulate breakage during driving.

1.5 Outline of the report

The rest of this report is outlined as follows. Chapter 2 explains the electronics of the ECU and the control of the clutch. Chapter 3 outline what tools were used and how they work. Chapter 4 describes the implementation of the measurements and construction of the new actuator configuration, Chapter 5 shows the results, and Chapter 6 discusses and compares the old versus the new test rig.

2. Background

Testing the software is not only part of the final steps of the development but also a part of the development process to assess the impact of changes, measure the performance of new modules and give feedback to the software engineers. Before new baselines or releases can be made, the software must undergo extensive testing. Also demands from customers affects how the testing is done. A hardware-in-the-loop test rig was not used during the development of the first generation of the clutch for example, but the increasing amount of electronics and software in the clutch lead to the needs for it.

2.1 Hardware-in-the-loop testing

When testing and developing real-time embedded systems, it is not always convenient to use the complete plant that the embedded system is supposed to control. Instead, a test platform combined with hardware parts of the plant with complex dynamics is used. Using hardware-in-the-loop testing (HIL) [15] cuts down costs, shortens the time to market and increases safety. Alternative approaches besides using the complete plant or parts of it is to simulate all dynamics. This will however be more of an approximation.

For the GEN V clutch, developing and testing the embedded system in a real car without HIL would increase the cost and development time. The clutch has too complex dynamics to be replaced by simulated models. This is why a test rig with a simulated car combined with the real clutch is used. This setup utilizes the simplicity of a simulated car but it still keeps the real world complex dynamics.



Figure 2.1. The test rig.

2.2 The test rig

A HIL software test rig for the GEN V clutch is shown in Figure 2.1. The test rig consists of a set of modules: the device under test (DUT), actuators, an external hardware for fault injection, a power supply and a measurement and control system which are fitted together in a 19" rack. A block schematic of the test rig is shown in Figure 2.2. Its various components are described below.

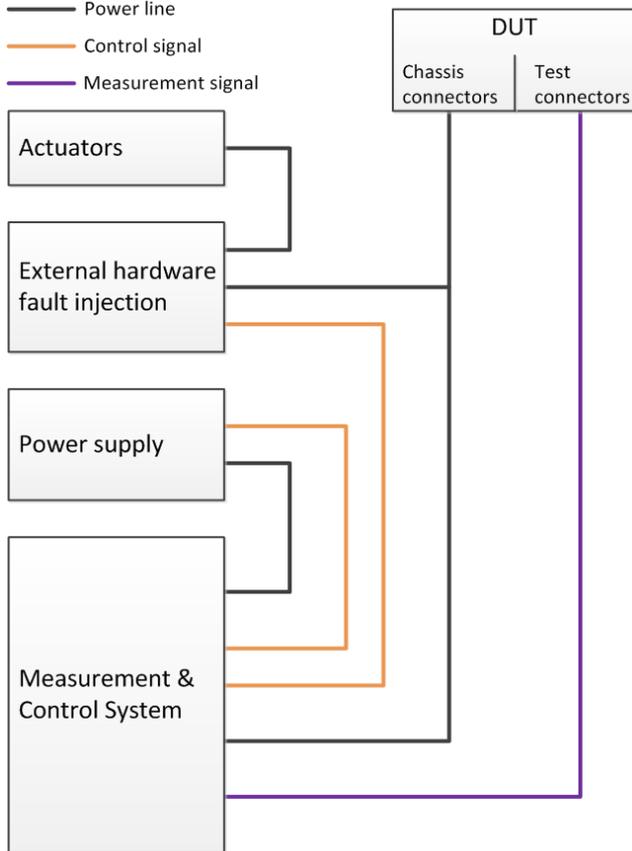


Figure 2.2. Block schematic of the test rig.

- The **device under test (DUT)** is the ECU with the chassis connectors being the connectors that would normally connect it to the vehicle, and the test connectors are additional connections needed for measurements.
- The **actuators** include the types normal, stuck axle, high pressure and low pressure. All faults are mechanical faults, and relays are used to switch between them. For test purposes in the rig, the actuators are mounted onto a

pump block instead of a real clutch. A pump block is a simplified aluminum housing filled with hydraulic fluid.

- The **external hardware fault modul** can inject an open circuit (pump disconnected) and five different short circuits.
- The **power module** supplies the ECU with the power needed to drive the motor.
- The **measurement and control system** is implemented using a VT System from Vector Informatik. The VT System is basically the heart of the test rig, controlling the power module and simulating the vehicle with all its CAN nodes. The user controls the VT System via a PC where the automated tests are programmed in CANoe, and the simulation is then run on the real-time module in the VT System.

CANoe is the software that comes with the VT System and is used for practically everything concerning the test rig. It uses a C-like programming language called CAPL to program the different simulated modules in the simulated CAN network.

The focus of this work will be on the actuator module. If for example the test case is about simulating a hardware fault when driving the vehicle, then the normal actuator must be switched to the faulty actuator. This creates characteristics not found in the real world since the faulty actuator is at stand still when enabled.

2.3 The ECU interface

There is no feedback in terms of hydraulic pressure from the actuator to the lamellas. Instead the current to the actuator is measured, and, depending on the pressure set point and other variables, a voltage that is fetched from a table with charted values is then applied.

The current is measured between the LS-transistor and ground via a shunt, see Figure 2.3. The maximal current that can be measured is 25 A. Also there is a transistor in the middle, which is used as a diode to make sure that current can flow in the reverse direction in case when the voltage becomes negative on the

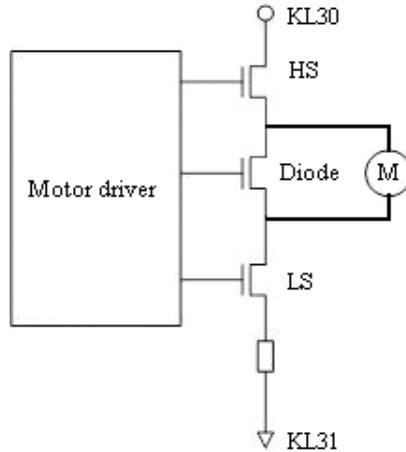


Figure 2.3. Connection between the ECU and the motor.

positive side of the motor. The LS-switch is always conducting, except when a forced shut down of the clutch is needed.

Controlling the voltage to the motor is achieved by switching the HS-transistor at 10 kHz, yielding a square wave voltage to the motor. By changing the duty cycle from the ECU with pulse width modulation (PWM), the average voltage to the motor is controlled, see Figure 2.4.

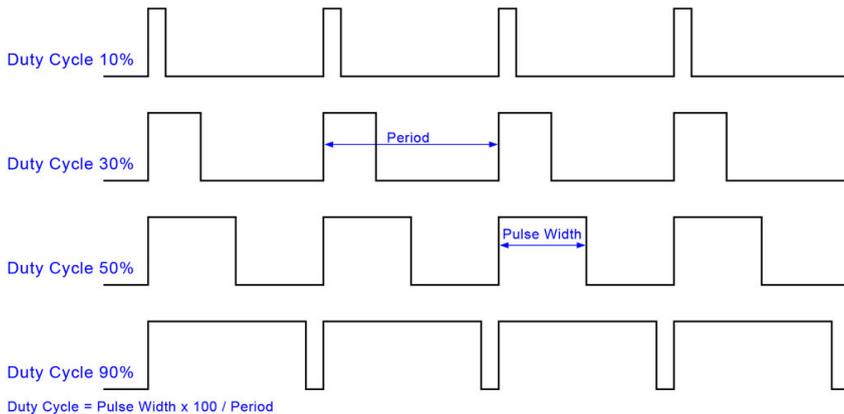


Figure 2.4. Pulse width modulation.

2.4 Motor and pump

The motor in the clutch is a non-salient 2-pole brushed DC-motor with permanent magnets and operates up to about 5000 rpm. The pump is an axial piston pump with a centrifugal pressure regulator that is mounted onto the motor. Together they make up the electro-hydraulic actuator used to control the clutch. The terminal resistance is the single parameter that deviates the most between two motors because of the carbon brushes to the commutator. This should be taken into account as an error source in the measurements. Also during the lifetime of the clutch, parameters might change slightly. To make sure that the performance is consistent over time, the ECU makes an automatic calibration every once in a while, adapting and compensating for minor hardware changes.

3. Equipment

The use of different equipment was divided into different activities.

For measurements on the old actuators and processing of the data, the following items were used: An oscilloscope, a wave generator, two power supplies, an NI cDAQ-9178, a differential amplifier, a current sensor amplifier, a hall current sensor and a PC with LabVIEW for data collection. For processing of the measurement data, MATLAB was used.

For controlling the ECU, a CAN-USB converter was connected to the PC with a program to set the pressure setpoint of the pump. There were three different pumps on which the measurements were conducted: a normal pump, a high pressure pump and a stuck axle pump.

For simulations, Simulink with a complete GEN V simulation model (provided by the company and modified for the purpose of this work) was used.

For the electronics, StripCad was used for the circuit layout and a soldering iron was used for the build.

For implementing and testing the new actuator, CANoe was used for programming the fault injection models. A VT System was used to simulate a car with all its nodes and to test the new injection module.

4. Implementation

The implementation is divided into several activities, where the first step is to build a set of faulty actuators for measurements. The next step is to set up a measurement system to measure the behavior of the faulty pumps in terms of voltage and current.

4.1 Building the faulty pumps

To obtain a motor with stuck axle a hole was drilled through the motor housing and a screw was screwed through the hole that rested against the axle, which prevented the axle from rotating.

The high pressure variant was created by placing distances under the centrifugal arms, making them unable to close fully, directing excessive pressure to the clutch.

The low pressure configuration was left to be dealt with in the end of the thesis if there was time left over.

4.2 Measuring the characteristics

The voltage and current characteristics at the motor terminal should be identified. For the current, this includes the average value as well as the commutating pattern, which can be seen as six wave tops for every revolution of the motor.

A fourth degree low pass filter was used to take out the high frequency parts that are not of importance to look at. Therefore a fourth degree lowpass filter with the poles placed in Butterworth formation with a quality factor of $1/\sqrt{2}$ and cut off frequency at 1 kHz was designed. The online filter calculator [4] assisted in the calculations. Two filters were made.

For the measurement of the voltage and current characteristics of the actuators, a measurement setup consisting of a power supply to the ECU, a voltmeter, an ammeter and a NI cDAQ-9178 data acquiring system connected to the voltmeter and ammeter was used, see Figure 4.1. One filter was then placed between the ammeter and the NI-system, and the other filter was placed between the voltmeter and the NI-system.

The NI-system was then connected to a PC where a program in LabVIEW was created to sample and acquire the measurement data.

KL30 and KL31 are connected to the ECU and the positive and negative connections from the ECU are connected to the differential amplifier whose output goes to the NI-system where data is acquired. To measure the current, a hall sensor surrounding the positive connection from the ECU is used and amplified by the current sensor amplifier connected to the NI-system.

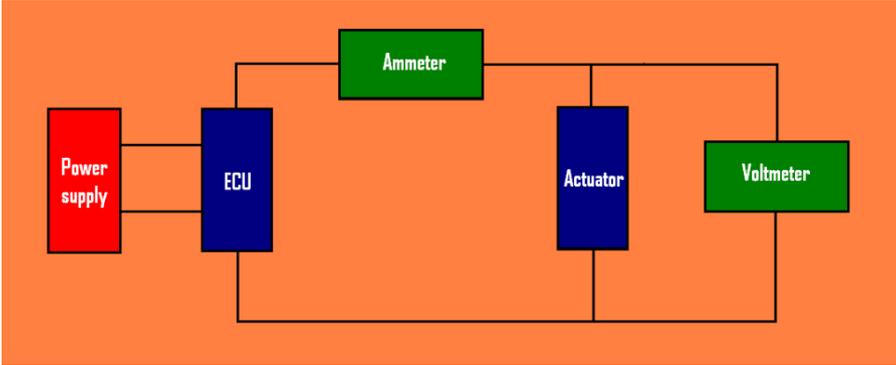


Figure 4.1. Block schematic of the measurement setup.

For each one of the three configurations, the following step responses were performed and measured:

- Pump off -> pump on -> pump off.
- Pump on -> 5 bar -> pump on.
- Pump on -> 20 bar -> pump on.
- Pump on -> 40 bar -> pump on.
- 5 bar -> 20 bar -> 5 bar.
- 25 bar -> 30 bar -> 35 bar -> 40 bar -> 35 bar -> 30 bar -> 25 bar.

The responses were sampled during 10 seconds with 100 kS/s and saved as text files, which were then imported to MATLAB for further processing, plotting and calculations.

A MATLAB script was written to synchronize two measurement series with each other. If for example the measurements for the normal and stuck axle configuration are to be compared, the measurements when plotting in MATLAB need to start at the same time for easier comparison. To do this, the rising edges of the two steps were first located for both measurements. Then a suitable number of samples in the beginning and the end of the measurements were deleted in order to make them the same length. No essential data was lost with this method since the step response was made in the middle of the 10 second sample period.

4.3 Interpreting the measurement data

With the measurements between two configurations synchronized and plotted, the differences could now be analyzed and interpreted. The next step was to design an electrical device that could inject the observed differences in the measurements.

One design idea that came up was to put a circuit in parallel with the motor, thus making the motor, seen from outside, drawing more current. And since the rotation speed impacts on the current shape, a voltage source in series with the motor is needed to keep the same rotation speed as a faulty pump. Figure 4.2 shows the measurement system with the new actuator and the electrical circuits.

Questions that needed to be answered before building the electronics were for instance:

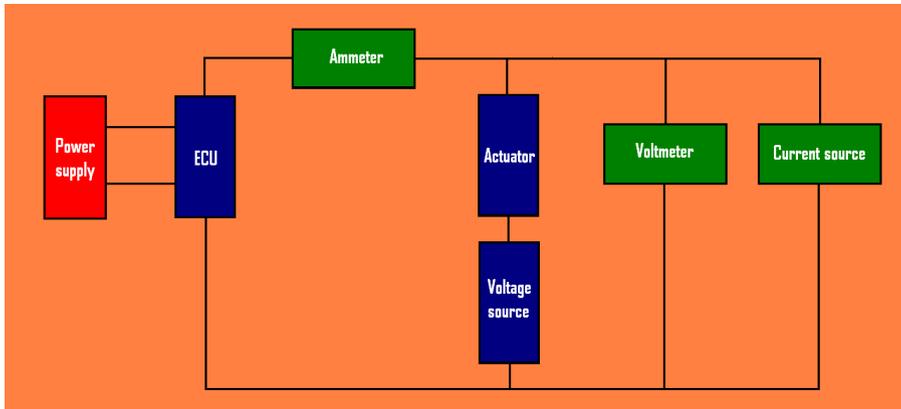


Figure 4.2. Block schematic of the new actuator with electrical circuits.

- How much current and power must the circuits be able to withstand?
- What voltage (and when) needs to be injected by the voltage source to match the rotation speed of a certain faulty pump?
- What current needs to be conducted through the parallel path and when?

The case with the stuck axle is where the actuator draws the most current since the load is the hardest to rotate. Therefore the measurements from this case gave the upper boundary of how much current the electronics needed to withstand. The lower boundary for the current source is 0 A.

If the motor is prevented from rotating while the ECU applies maximum voltage, the maximum voltage that the ECU can output must be the upper boundary for the voltage source in series. The lower boundary for the voltage source is 0 V.

Interpreting the measurement data, simulating and building the electronics are all somewhat tied together, so the design has to be done in an iterative fashion.

4.4 Simulations

One straightforward way to make the new configuration look like a faulty one would be to use the measurement data of the faulty configuration as a reference value, measuring the states and using a regulator to make the states follow the reference.

Another way to do it would be to find a model for the difference between the normal and faulty configuration, and this is the solution that was chosen in the end. The current characteristics of two different actuators might not be exactly the same, and using a model for fault injection would be much easier.

To make the process of finding an appropriate model easier, a Simulink model of the clutch was used to try out different fault injections and see what the result was. Firstly, the rotation speed between the normal and high pressure configuration was attempted to be matched. The back EMF, V_e , is proportional to the rotation speed, ω ,

$$V_e = \omega \times K_e,$$

where k_e is the back EMF constant of the motor.

This means that the faster the DC-motor spins, the larger the back EMF will be. For instance, with the high pressure pump the rotation speed will be lower, since the load is larger due to the increased pressure it is creating.

From the measurements of the voltage and current it is now possible to calculate the rotation speed for the different configurations and pressure setpoints. The back EMF constant is looked up in the data sheet from the manufacturer of the motor [7]. Using the relationship

$$V_0 = I \times R + V_e$$

where V_0 is the terminal voltage, I is the current and R is the terminal resistance (which can be found from the datasheet of the motor [7]), V_e could be calculated and also the rotation speed for comparison between the actuators.

There is a small difference between the normal configuration measured in reality with the pump block and the normal configuration in Simulink. Part of this difference comes from the fact that the simulation uses a real clutch instead of a

pump block. Exactly what the difference looks like were not fully investigated although the differences can be seen in the results.

The measured voltage characteristics were imported to MATLAB and used in Simulink.

The next step was to match the simulated rotation speed of the simulated normal actuator with an input voltage from a real faulty actuator to the rotation speed of a simulated normal pump with an input voltage from a real normal actuator. To match the rotation speed, a simulated voltage source was implemented and different voltage step profiles were injected to find a good approximation. To find an exact voltage model between the actuators would be too much work, so temporarily, voltage steps were used to approximate the rotation speed difference between two actuators.

To match the current characteristics, a simulated parallel current source was implemented and different current steps were injected in the same fashion as for the voltage source.

4.5 Implementing a model for injection

After trying some different implementations in the simulation environment it became clear that using voltage and current steps as a model for injection was simple to implement and worked as a good approximation. The solution is not perfect but anything more advanced would take more time to implement and tune. The applied voltage from the ECU is measured in order to know when to inject the steps. It is explained in the pseudo code below. For instance, injecting 2 V in series and 7 A in parallel for the high pressure actuator at a 40 bar pressure setpoint was a good approximation according to the simulations. The pseudo code for this would be:

```
if ( $V_{ecu} \geq 2\text{ V}$ ) {  
     $V_{series} = 2\text{ V}$ ;  
}  
else {  
     $V_{series} = V_{ecu}$ ;  
}  
 $I_{parallel} = 7\text{ A}$ ;
```

To make the actuator behave like a stuck axle actuator, the motor should not rotate and therefore should the applied voltage from the voltage source follow the applied voltage from the ECU. This way the voltage over the motor becomes zero and the current source should approximate the current shape of the stuck axle measurement. The pseudo code for this would be:

$$I_{\text{parallel}} = 40 \text{ A};$$
$$V_{\text{series}} = V_{\text{ecu}};$$

Finally, the normal actuator pseudo code would be:

$$I_{\text{parallel}} = 0 \text{ A};$$
$$V_{\text{series}} = 0 \text{ V};$$

For all the different pressure set points for the high pressure actuator, voltage and current levels will be chosen accordingly.

4.6 Building the electronics

There were a couple of possible alternatives for building the electronics. The chosen solution for the voltage source was a P-channel MOSFET transistor between the negative side of the motor and ground (KL31), see Figure 4.3. A transistor capable of handling the maximum predicted power was chosen. The

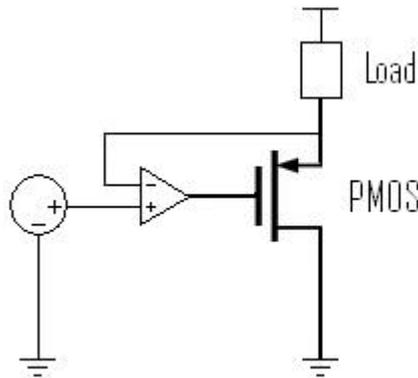


Figure 4.3. Voltage source circuit.

voltage across the transistor is controlled by an OA with negative feedback. If for example the voltage across the transistor is lower than the reference value at the positive input of the OA, this difference will be amplified yielding a greater voltage at the gate of the transistor which will close it a little more than it was before raising the voltage across it. In this case, a totally closed transistor means no current, and an open transistor means maximum current. Greater voltage at the gate of a P-channel will close it more, but a greater voltage at the gate for an N-channel will open it more. Because of the feedback loop, the circuit is self regulating. Also it is important that the voltage settles quickly in the step response without too much oscillation.

We now proceed to the current source, see Figure 4.4. If a parallel circuit is to be used, the current through this path needs to have the same inductance as found in the motor, so the decision was made to use an armature found in the DC-motor and solder connections to it.

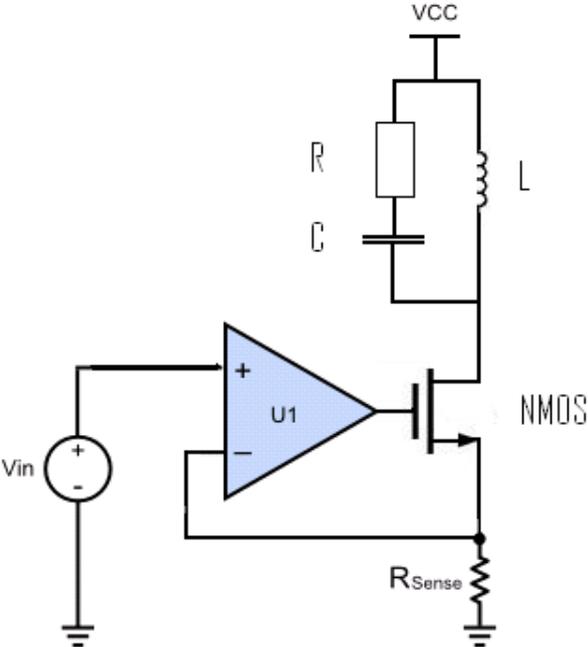


Figure 4.4. Current source circuit.

To control the amount of current passing through this path, a voltage controlled current source realized with an N-channel MOSFET transistor and an OA with negative feedback and a feedback resistor was chosen. To cope with the calculated maximum power dissipation from the measurements, four of them were connected in parallel, thus sharing the total power.

A signal from a wave generator was initially used as a reference value, which will be replaced by signals from the VT System later. When first trying to realize the current source, the circuit did not find steady state and the voltage across the feedback resistor started to oscillate. According to the data sheet [9], oscillations can occur when there is inductance in the current source. The solution is to add a resistance and a capacitance in parallel with the inductance, and once this was implemented the voltage became stable. The step response was not as good as for the voltage source but at least it did not oscillate.

The power over the feedback resistor in the current source is calculated as

$$P = U \times I.$$

If a maximum of 10 V was to be used from the VT System directly on the input of the OA, thus getting 10 V over the feedback resistor with a maximum current of 50 A, the power developed in the resistor would roughly equal 500 W. So to keep the power down the voltage was split up so that 10 V maximum equals 0.5 V on the input of the OA.

With a maximum of 0.5 V over the feedback resistor and a wanted maximum current of 50 A, the feedback resistor calculates to about 0.01 ohm. To make sure that the resistors can handle the power, we used four 0.05 ohm resistors in parallel which, according to the data sheet [13], will be able to handle the power. A DC-DC converter [12] was used to power the OA circuit [14].

The applied voltage V_{in} will appear at the source of the transistor when steady state has been reached. Since the operational amplifier magnifies the difference between V_{in} and the voltage at the source of the transistor, the difference will lead to a higher voltage at the gate of the transistor, which in turn opens the channel between drain and source, leading to a higher current and a higher voltage across

the feedback resistor. So if a certain voltage to V_{in} is applied, after some time the current source has automatically found the equilibrium thanks to the negative feedback.

4.7 Adding the configuration to the VT System

An important part of the electronics construction is making it compatible with the VT System.

In the users manual [8] the DA-converter that is used is rated at 0-10 V on the output and a maximum current of 200 mA. But the maximum of 10 V must be scaled down to 0.5 V for the OA to the current source, since a lower voltage over the feedback resistors will result in less power development in the resistors, preventing them from reaching their power dissipation limit. A simple voltage divider, see Figure 4.5, was therefore implemented.

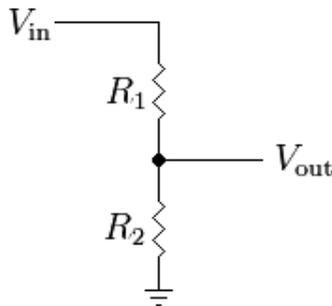


Figure 4.5. Voltage divider.

The VT System has a maximum of 200 mA on the output and therefore $R_1 = 10\text{ k}\Omega$ and $R_2 = 470\Omega$ were chosen in the voltage divider to prevent the current to the OA reaching the VT System's limit.

To be able to inject the correct faults at the right time, it is necessary to measure both the terminal voltage at the motor and the current drawn from it and for this the built in AD-converters in the VT System was used to convert the measured signals and use the values for the timing of the fault injection. The voltmeter and ammeter are implemented in the same fashion as for the measurement setup used

previously, i.e, voltage is measured between the positive and negative side of the ECU and the current is measured in series with the positive side of the ECU.

The models which were developed with the simulations were then implemented in CANoe and uploaded to the VT System. Step responses with 40 bar pressure setpoint were then made to each one of the new models and the characteristics were measured.

5. Results and discussion

A selection of the measurement and simulation results are displayed in this section for comparison and explaining purposes.

5.1 Measurements – old actuators

Figures 5.1 to 5.3 show the results from step responses with a pressure setpoint of

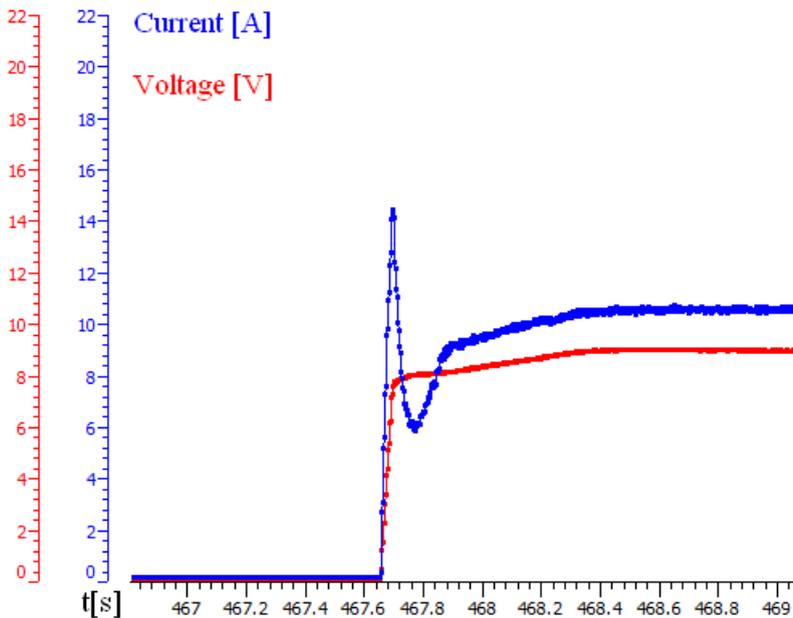


Figure 5.1. Normal characteristics.

40 bar for the three fixed configurations. These measurements are the basis for the models for the new actuator.

As seen in Figure 5.1, the actuator is switched of in the beginning, then a 40 bar pressure step rises the voltage according to a charted value. Since the rotation speed is low in the beginning, the back-EMF is therefore low and the actuator will draw much current as seen by the peak value. Then the rotation speed increases and the current sinks, the ECU senses the drop in current and increases the voltage gradually until steady state has been reached.

In Figure 5.2 we see that higher pressure means a larger load for the motor, and a larger load decreases the rotation speed which then leads to a decreased back-EMF and the motor will draw more current than normal. To keep the current at the same level as for the normal actuator, the ECU tries to compensate by lowering the

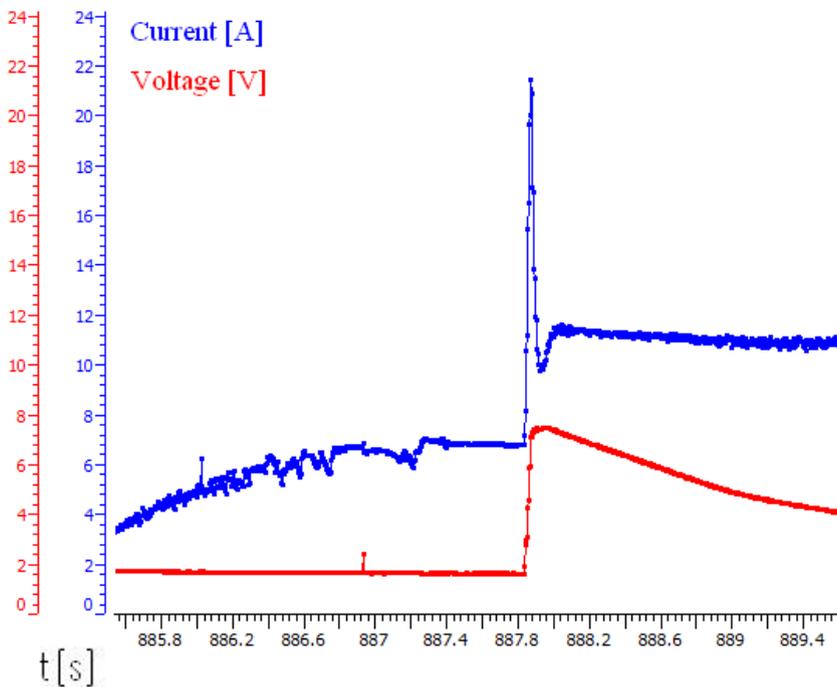


Figure 5.2. High pressure characteristics.

applied voltage to the motor. This characteristic with the gradually sinking voltage should be mimicked by the new high pressure actuator.

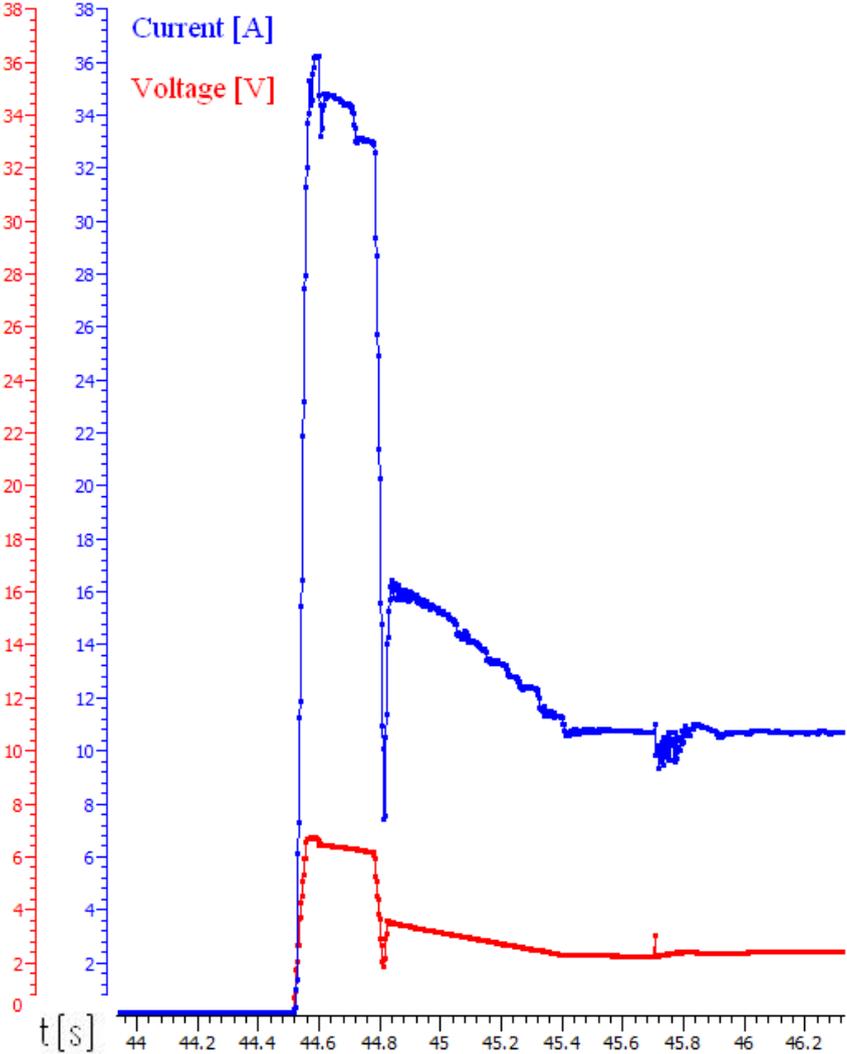


Figure 5.3. Stuck axle characteristics.

Finally, Figure 5.3 shows the stuck axle characteristics. This case will be seen as the largest load for the ECU. The rotation speed is zero which means no back-EMF and thus a large current.

5.2 Simulations

First, graphs with comparisons between measured and simulated characteristics under the same conditions are displayed to show the deviation when simulating. After that a selection of graphs attempting to mimic faulty actuators with a normal actuator with additional current and voltage injected are shown.

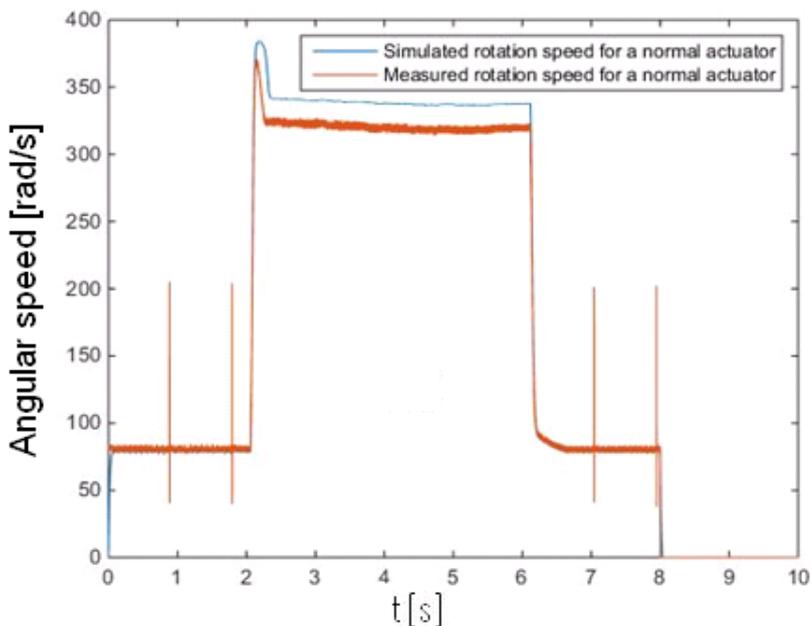


Figure 5.4. Comparison between simulated normal and measured normal.

The graph in Figure 5.4 shows the simulated rotation speed for a normal actuator and the second graph shows the normal rotation speed according to the measurement. They both have the same applied voltage to the motor terminal. There is some difference in steady state where at least one of the responsible factors is the resistance that changes continuously. In the Simulink model, the resistance was temperature dependent and changing. When calculating the rotation

speed from the measured voltage and current a fixed resistance value from the motor data sheet was used [7].

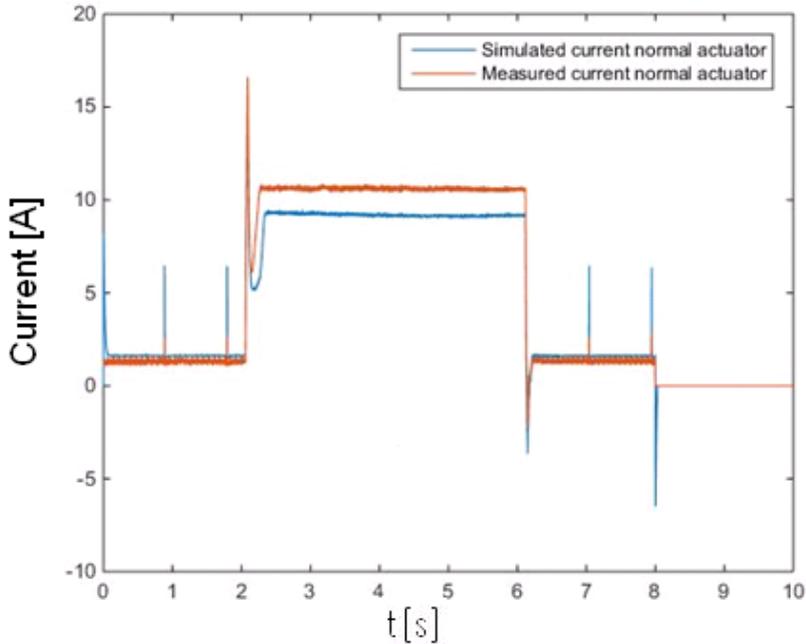


Figure 5.5. Current comparison normal actuators.

Figure 5.5 compares the drawn current from a measured normal actuator with a simulated normal actuator under the same conditions. Again, the resistance might be the largest error source under steady state.

The graph in Figure 5.6 shows the simulated normal rotation speed with 2 V in series and the desired motor rotation speed according to the measurements. When the actuator is only activated with 0 bar pressure set point the rotation speed is very similar between the two. The peak value for the measured rotation speed is slightly higher and can be derived from the error between simulation and measurement. Here the final model for the high pressure actuator was used, i.e., when the voltage in the simulation exceeds 2 V, the voltage source becomes 2 V. It was a good enough approximation and relatively easy to implement.

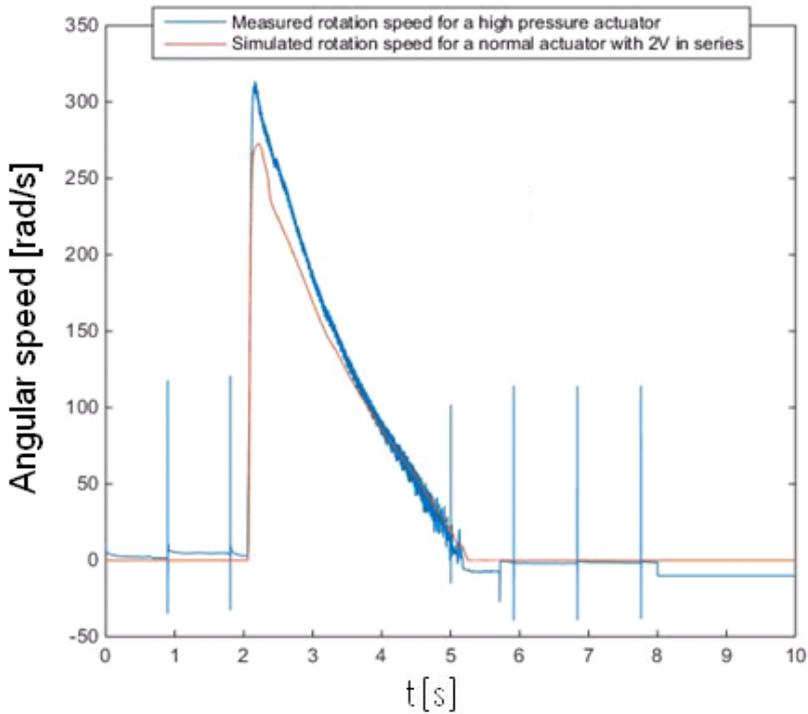


Figure 5.6. Rotation speed comparison for high pressure.

Figure 5.7 compares the measured drawn current from a high pressure actuator with the simulated drawn current with the final model used. The injected current shall be 7 A when imitating a high pressure actuator. The drawn current from the simulated high pressure actuator almost converges with the real high pressure actuator at 0 bar pressure set point. However when the pressure step comes, the current drops in the simulation which means that a better model for current injection is needed here.

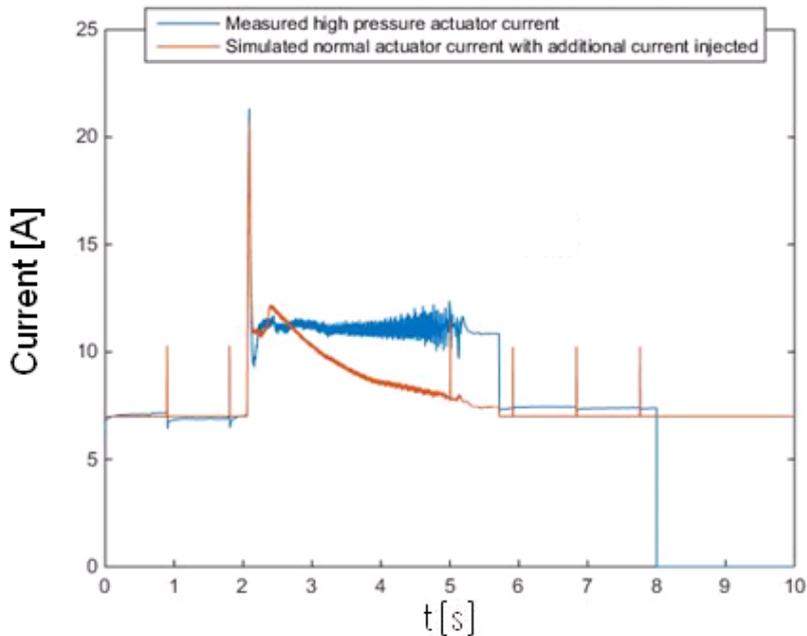


Figure 5.7. Current comparison for high pressure actuators.

5.3 The new injection module

The circuit layout in Figure 5.8 was made in StripCad to see the finished layout before trying to solder everything together on the circuit board. Also the transistors are screwed to a heat sink for cooling. Connections are placed on the edge for easy connection to the test rig.

Measurements in Figure 5.9, 5.10 and 5.11 show a normal actuator with the fault injection circuits connected to simulate different actuators. These should be compared to the measurements of the old actuators since these were the goal to resemble.

Figure 5.9 shows the new normal actuator which should be completely identical to the old normal actuator. The only error source is the voltage source which, from measurements, did not drop all the way to 0 V.

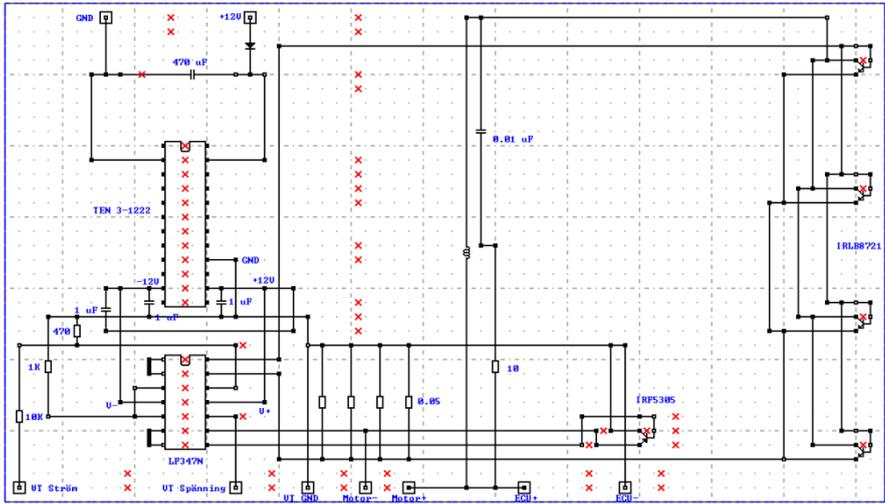


Figure 5.8. Circuit layout for the new injection module.

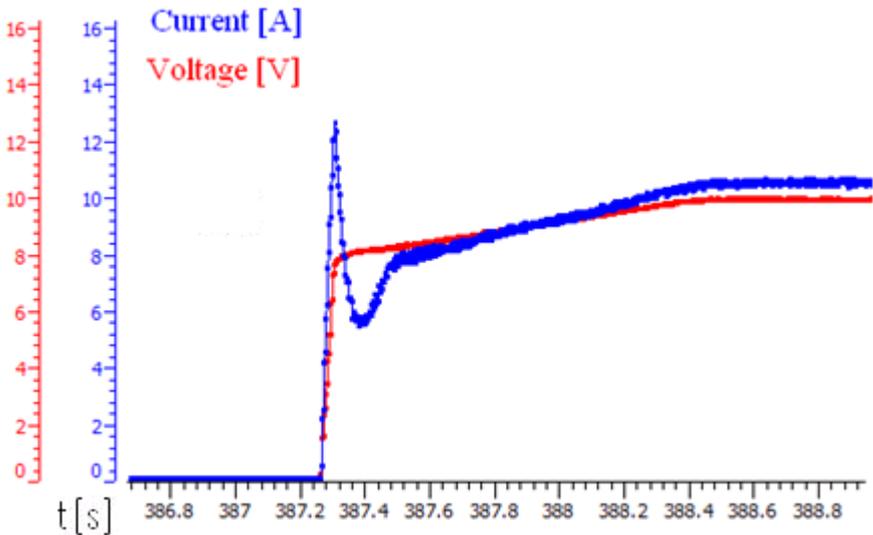


Figure 5.9. New normal actuator.

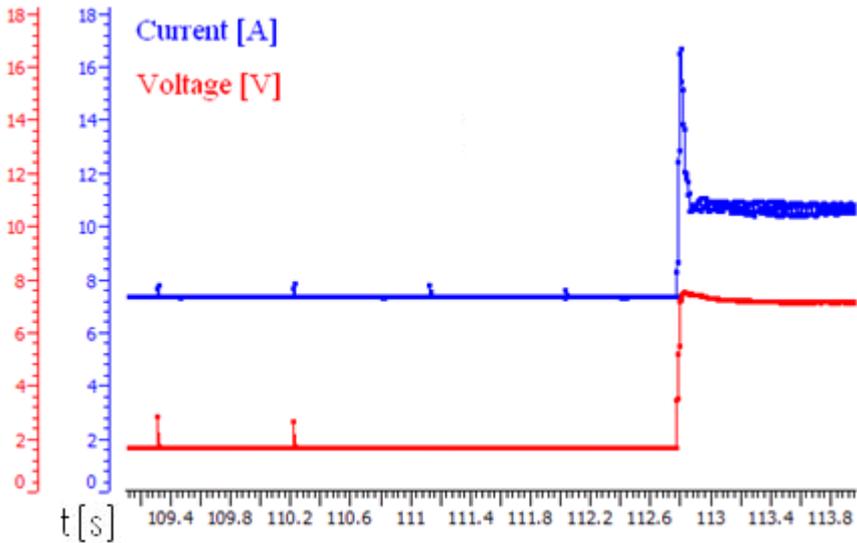


Figure 5.10. New high pressure actuator.

Figure 5.10 shows the new high pressure actuator. The voltage does not drop as it does for the old high pressure actuator, that means that gradually more current must be injected in order for the ECU to compensate with a lower voltage. A more advanced injection model would solve this. Finally, Figure 5.11 shows the new stuck axle characteristics.

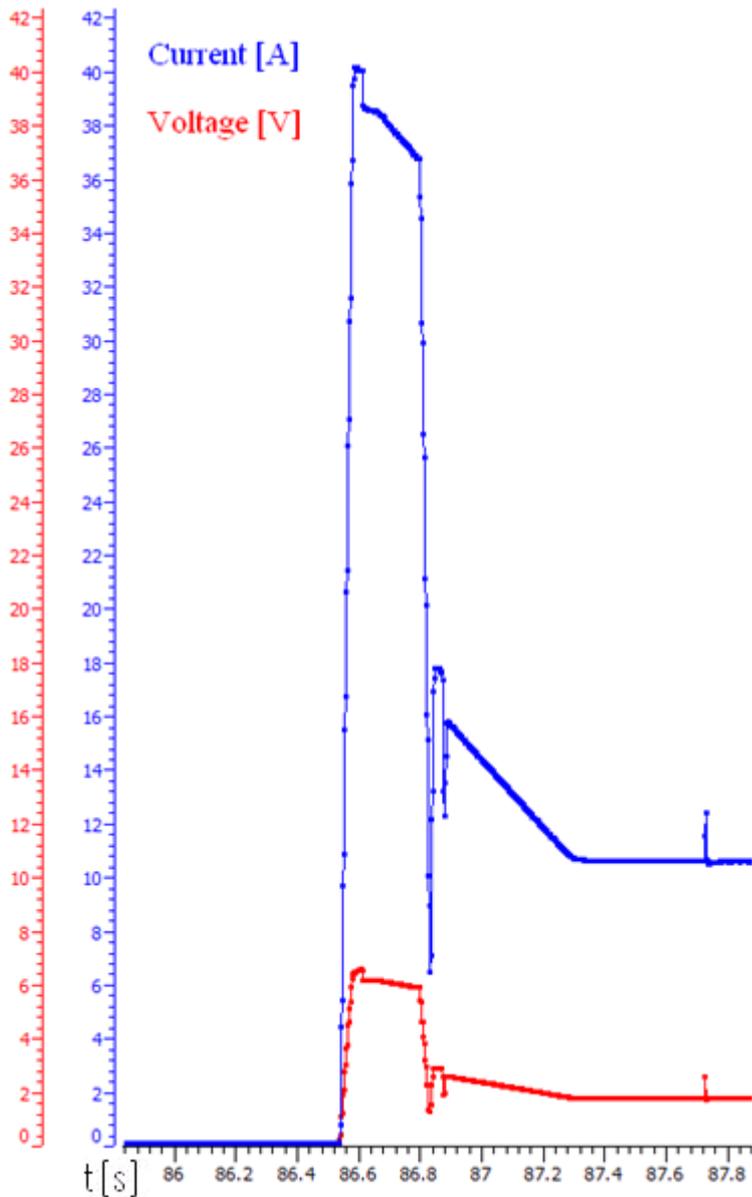


Figure 5.11. New stuck axle actuator.

5.4 Comparison between the old and the new system

The voltage source in series could not completely reach the lowest boundary 0 V, which will slightly impact on the new normal actuator characteristics. This was caused by the characteristics of the chosen transistor. Other than that, the new normal actuator is very similar to the old normal actuator.

Regarding the high pressure actuator, from the beginning it could be seen that a more advanced model was needed to correctly imitate the high pressure characteristics. This actuator is the one that deviates the most from the wanted result as can be seen by the measurements. The parallel current source needs to increase the current gradually to force the ECU to compensate and drop the voltage like it did for the old high pressure actuator.

The new stuck axle actuator has satisfying characteristics. The shape looks almost identical to the old stuck axle except for the current amplitude, which is slightly larger than before. Applying 35 A to the current source did not give the correct shape. Applying 40 A did however give the correct shape except for the current exceeding the old stuck axle's peak current value.

6. Conclusion

The new normal actuator fulfills the requirements, although a better solution for the voltage source could be found to make the voltage source able to drop to 0 V. As could be seen in the final graph for the new high pressure actuator, it did not quite reach the requirements since the shape was too different from the real high pressure actuator. The stuck axle had satisfying results with a very similar shape except for the peak current value. For the software testing, using the electrical stepless fault injection as a compliment to the old fixed actuators could be a good combination since they are good at different things.

Future work

Some ideas for future work include being able to simulate low pressure with a mechanical solution and finding a better model for the high pressure actuator where the current source can inject more current if it senses that the voltage does not drop. Also, new models for other types of failures could be investigated.

Bibliography

- [1] Per Söderberg. *Gen5 Full Software Test Rig Documentation*. BorgWarner, 2014.
- [2] *Presentation TTT utbildning_Mar2014.pptx*. BorgWarner, 2014.
- [3] *Analog filters*. URL: <http://www.analog.com/library/analogdialogue/archives/43-09/edch%208%20filter.pdf> (visited on 02/19/2015).
- [4] *Online filter calculator*. URL: <http://sim.okawadenshi.jp/en/OPstool.php> (visited on 02/19/2015).
- [5] *DC Motor calculations*. URL: <http://www.micromo.com/motor-calculations> (visited on 03/30/2015).
- [6] *N-channel transistor IRLB8721PBF*. URL: <https://www.adafruit.com/datasheets/irlb8721pbf.pdf> (visited on 04/18/2015).
- [7] *Data sheet of DC-motor*. motor.pdf, Spezifikation 7.13.225.406.00. Motor manufacturer, 2013.
- [8] Vector Informatik. *User manual VT System Version 1.7*. Vector Informatik GmbH, 2012.

- [9] *Inductive load arc suppression*. URL:
<http://www.hamlin.com/specSheets/AN108A-Inductive-Load-Arc-Suppression.pdf>, page 2 (visited on 05/15/2015).
- [10] *Deriving and implementing a Model of the Fifth Generation Haldex AWD actuator*. URL: https://www.iea.lth.se/publications/MS-Theses/Full%20document/5283_full_document.pdf (visited on 03/05/2015).
- [11] *P-channel transistor IRF5305*. URL:
http://www.redrok.com/MOSFET_IRF5305_-55V_-31A_6mO_Vth-4.0_TO-220.pdf (visited on 04/18/2015).
- [12] *DC-DC converter*. URL:
<http://www.farnell.com/datasheets/1806537.pdf> (visited on 04/30/2015).
- [13] *Shuntmotstånd*. URL:
https://www1.elfa.se/data1/wwwroot/assets/datasheets/yrOAR_data_e.pdf (visited on 05/08/2015).
- [14] *OP AMP*. URL: <http://www.ti.com/lit/ds/symlink/lf147.pdf> (visited on 05/02/2015).
- [15] *Hardware-in-the-loop testing*. URL:
<http://www.adi.com/technology/tech-apps/why-use-hardware-in-the-loop-simulation/> (visited on 06/12/2015).

| | | | |
|---|---------------------------------------|--|-------------|
| Lund University Department of Automatic Control Box 118 SE-221 00 Lund Sweden | | <i>Document name</i> MASTER 'S THESIS | |
| | | <i>Date of issue</i> June 2015 | |
| | | <i>Document Number</i> ISRN LUTFD2/TFRT--5983--SE | |
| <i>Author(s)</i> Erik Jönsson | | <i>Supervisor</i> Per Söderberg, BorgWarner TTS AB Anton Cervin, Dept. of Automatic Control, Lund University, Sweden Karl-Erik Årzén, Dept. of Automatic Control, Lund University, Sweden (examiner) | |
| | | <i>Sponsoring organization</i> | |
| <i>Title and subtitle</i> Stepless fault injection for electrohydraulic actuator | | | |
| <i>Abstract</i> <p>One of the cases for testing the BorgWarner GEN V clutch is to see if pump and motor malfunctions are detected by the software. Until now there have been a couple of fixed configurations testing clutches with different faults. The goal was to investigate if these configurations could be replaced by a normally functioning motor and pump connected to electrical circuits to mimic faulty clutches, which would ultimately lead to more flexibility during the testing. The work has been carried out at BorgWarner TTS in Landskrona.</p> | | | |
| <i>Keywords</i> | | | |
| <i>Classification system and/or index terms (if any)</i> | | | |
| <i>Supplementary bibliographical information</i> | | | |
| <i>ISSN and key title</i> 0280-5316 | | | <i>ISBN</i> |
| <i>Language</i> English | <i>Number of pages</i> 1-46 | <i>Recipient's notes</i> | |
| <i>Security classification</i> | | | |