Ethanol electronic fuel pump control

Gilvana Prestes [1]
Artemys Louise Onotera [1]
Thiago Bastos Fernandes [1] [2]
[1] Robert Bosch ltda. – Powertrain Solutions
[2] Universidade Tecnológica Federal do Paraná – UTFPR – PPGEM

ABSTRACT

Carbon reduction and energy efficiency have become critical priorities for the corporate sector, prompting companies to develop and adopt sustainable alternatives to minimize emissions. This shift raises important questions about the efficiency and evolution of internal combustion engines designed to run on alternative fuels alongside traditional energy sources.

Considering the growing demand for sustainable fuels, ethanol emerges as a key solution in reducing emissions in the transportation sector, particularly in South America, with Brazil leading global ethanol production through sugarcane agriculture. While ethanol has a lower energy density compared to fossil fuels like diesel, its higher-octane rating improves combustion efficiency, which partially offsets the energy difference. To make ethanol-powered technology viable, modern automotive systems increasingly rely on embedded electronic components to optimize fuel management and reduce pollutant emissions.

This study presents a technical feasibility of a closed-loop control system designed to enhance ethanol injector performance by regulating the fuel pressure. The experiment validated that pressure can be dynamically controlled by fine-tuning the PWM (Pulse Width Modulation) duty cycle in response to real-time operational conditions, with the pressure signal serving as a feedback mechanism in the closed-loop system. Using a scaled-down vehicle model, the study replicates actual vehicle components, ensuring simulation of system behaviors and phenomena for validation of this ethanol-based technology.

INTRODUCTION

Heavy haul transportation, which predominantly makes use of diesel-powered engines to transport substantial volumes of freight over extended distances, represents a significant source of greenhouse gas (GHG) emissions. The high energy demands associated with hauling heavy loads result in considerable fuel consumption, consequently leading to increased emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter. These emissions pose environmental hazards and contribute to air quality degradation and climate change.

Heavy-duty vehicles, encompassing trucks, trains, and marine vessels, account for a disproportionate share of transportation related GHG emissions, despite constituting a smaller fraction of the global vehicle fleet. Mitigating emissions in the heavy haul sector necessitates the implementation of innovative approaches, such as improving engine efficiency and adopting alternative fuels, including biodiesel, hydrotreated vegetable oil (HVO), liquefied natural gas (LNG), and ethanol, to partially - or completely - substitute diesel as the primary energy source.

In this context, alternatives for fuel consumption control are of significant interest, particularly from the perspectives of fuel efficiency, battery energy consumption, and atmospheric gas emissions. In vehicles, fuel pressurization systems typically operate continuously with mechanical pressure regulation. These systems are commonly connected directly to the battery after T15 signal, and they often feature substantial fuel return volumes to the tank, as the fuel pump operates at maximum capacity in any engine load or operational condition.

There are commercially solutions available to control the fuel pump flow rate. However, these application are focused on a single Electronic Fuel Pump (EKP), with particular attention to cold start conditions, starting with an approximate pressure of 6 bar and then reducing it once the engine reaches its operating temperature.

For applications requiring the combination of multiple pumps, an alternative for optimizing fuel injection involves adjusting the system pressure based on the engine's demand, ensuring that fuel is injected only when necessary, according to established consumption conditions. This approach leads to reduced fuel return to the tank, lower energy consumption, and controlled fuel usage.

It is in this context that the present study is relevant, as it investigates the development and implementation of a control system that regulates fuel injection by modulating the pressure of multiple commercially available EKPs. These pumps will be controlled through Pulse Width Modulation (PWM), generated by a signal generator, enabling precise control over the fuel delivery. This system ensures that fuel will be supplied in the appropriate quantity, based on the operational conditions of the vehicle, thus optimizing fuel efficiency, and minimizing energy consumption.

BIBLIOGRAPHIC REVIEWS

The development of the experimental and controlled implementation required the application of important concepts that will be reviewed with in the further topics.

PID CONTROLLER - A control system within a project is designed to retrieve data from a specified source and produce an output that may result from an event or phenomenon. To achieve a desired response from the system, it is often necessary to implement components that can adjust the system's behavior during operation [1]. In this context, controllers or control systems serve as these components, receiving information regarding a measured variable (which may vary by application, such as volume, pressure, or voltage, e.g.), and based on this measured variable, the controller adjusts the system's behavior [2].

Controllers can be configured in various forms, including mechanical, electrical, electronic, pneumatic, hydraulic, or combinations of them. As noted by Ogata [1], a variety of electronic controllers are available for implementation within a system; however, the selection of the appropriate type is contingent upon the output required by the system and the necessary interactions between the output and the setpoint pertinent to the application. Additionally, the author references that commonly utilized electronic controllers are the proportional (P), the integral (I) and the derivative (D) and its various combinations. Pinheiro [3] indicates that combination PID or PID adaptations account for approximately 50% of controllers employed in industrial applications.

A PID controller within a dynamic system computes the “error” as the difference between the actual output of the controlled variable and the desired value (defined setpoint). Based on this error signal, the controller generates an output control signal designed to minimize the deviation from the setpoint [2]. This control mechanism adjusts the system output based on three components: the proportional, the integral and the derivative component.

In the proportional control strategy, the output is directly proportional to the error signal. In other words, this proportionality indicates that an increase in the active error results in a corresponding increase in the controller output. The P controller continuously adjusts its output based on the instantaneous error, aiming to minimize the difference and achieve the desired state of the system. This adjustment is related to a proportional gain, denoted as Kp, which optimizes the system's response. The P controller can be mathematically represented by the Equation 1.

$$P_{output} = Kp * e(t) \quad (1)$$

The P_{output} represents the controller output and e(t) is the error.

The integration of the integral (I) component into the proportional (P) controller results in the formulation of a proportional-integral (PI) controller. This strategy combines two distinct actions, the proportional and the integral response. The first action provides an immediate response that is directly proportional to the error contributing to error reduction. On the other hand, the integral action adjusts its output based on the integral of the error, acting in the accumulated error over time, facilitating the eliminating steady-state error and corrects persistent deviations that are not fully mitigated by the proportional action.

PI controller can be expressed by the Equation 2, that was implemented in the Arduino code to execute the tests.

$$PI_{output} = Kp * e(t) + Ki \int e(t)\, dt \quad (2)$$

PI_{output} represents the controller output and e(t) is the error, Kp and Ki are, respectively, the gains related to the proportional and to the integral actions.

Finally, the incorporation of a derivative action into the PI controller, results in the PID controller. This mechanism regulates the system output based on three components that perform complementary roles. The derivative action computes the derivative of the error, which means that it is based in the rate of change of the error. By analyzing this rate, the controller can anticipate trends in the system's behavior and smoothing the system’s response.

In Lages [4], the aggregate output of these three components is mathematically represented by the PID control equation, as detailed in Equation 3. In this equation, PID_{output} denotes the control output, e(t) represents the error at time, and K signifies the respective gains associated with each component of the PID controller (proportional, integral, and derivative).

$$PID_{output} = Kp * e(t) + Ki \int_0^t e(t)\, dt + Kd \frac{de(t)}{dt} \quad (3)$$

The K parameters facilitate the modulation of the output signal, optimizing the system's response to closely approximate the desired setpoint.

PULSE WIDTH MODULATION (PWM) - Pulse Width Modulation (PWM) is an electronic technique utilized to modulate the pulse width of an electrical signal, enabling precise power regulation to a device. According to [5] the

PWM system converts a digital input signal into a corresponding analog output, that is represented by a voltage pulse sequence, where each pulse width is determined by the signal amplitude. This pulse sequence generates a wave with a constant frequency that exhibits high and low states, and the ratio of the duration of the high state to the total period of the cycle (the sum of the high and low states) is referred to as the duty cycle. In other words, the duty cycle is the relation of the pulse width to the total period of the waveform 5]. Variations in the duty cycle directly indicate the amount of power delivered to the system.

METHODS AND MATERIALS

An experiment was conducted to validate the control proposed by this study. This experiment is focused on validating the concept that fuel pressure can be dynamically controlled by fine-tuning the PWM duty cycle in response to real-time operational conditions, with the pressure signal serving as a feedback mechanism in the closed-loop system. Using a scaled-down vehicle model, the experimental setup replicates actual vehicle components, simulating the system behaviors and phenomena for validation of this ethanol-based technology.

The practical experiment comprised an integration of hardware and software components. The hardware aspects included the fuel pump, pressure sensor, rail, injectors, and signal generator; while the software involved the code developed in a microcontroller, along with its interfaces and communication protocols. Figure 1 depicts a simplified schematic representation of control designed for the testing.

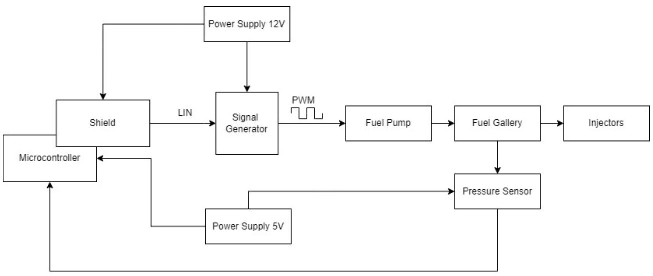

Figure 1. Experimental setup diagram

The control system implemented in this experiment consists of the interaction of a pressure sensor with a microcontroller and a signal generator. This signal generator interfaces with the microcontroller via a shield[1] that is equipped with three LIN (Local Interconnect Network) transceivers. These transceivers facilitate the conversion of digital signals to communication signals and vice versa [6].

The signal generator that receives the LIN messages generate the PWM signals to regulate the fuel pump, while the pressure sensor will provide continuous feedback to the microcontroller, in other words, the pressure sensor provides necessary readings, and the PWM signal is generated based on these inputs.

The pressure sensor is physically installed on the injector rail line via a derivation, enabling fuel pressure monitoring. It is electronically interfaced with the microcontroller through the designated terminals, facilitating the processing of pressure data and real-time adjustments by the microcontroller.

The hardware is powered by a 12V supply connected to both the shield and the signal generator, which in turn supplies energy to the fuel pump for its operation. A 5V power supply is also connected to the microcontroller for its operational requirements.

The subsequent sections will be dedicated to a discussion of the main components of the control system implemented.

PRESSURE SENSOR - The pressure sensor in this system provides real-time feedback of the pressure within the fuel rail. This data enables the microcontroller to dynamically modulate the PWM to adjust the pressure for optimal fuel injection performance, according to the engine demands.

In the scale-down experiment it was applied a commercially available resistive pressure sensor with an operational range of 0,5 to 16 bar.

In the system, the sensor employed has a measurement range from 0 to 5V, corresponding to digital values from 0 to 1023. The sensor acquires voltage readings and transmits this data to the microcontroller via an analog signal. The microcontroller processes the voltage signal using the Equation 4, where the resultant variable P represents the pressure value calculated. This formulation was derived from the sensor's characteristic curve and defined through the correlation between voltage and pressure using a linear regression model.

$$P = 3{,}875 * voltage - 1{,}4375 \quad (4)$$

FUEL PUMP - The Electronic Fuel Pump, also referred to as EKP (*Elektrische Kraftstoffpumpe*), is a component which primary function is to convert the electrical energy into hydraulic energy to transfer fuel from the tank to the injection system at the requisite pressure and

[1] Shield: Communication bridge between the microcontroller and the signal generator through LIN protocol.

amount of fuel regardless of variations in engine operating conditions [7].

The pump selected for the execution of the tests is a commercially available in-tank (submerged in the fuel) unit, operating at 12V, with a pressure testing of 5,5 bar and a flow rate of 100 L/h without the return of excess fuel back to the tank.

An EKP is composed of a series of components, including the electric motor and the impeller, that work to the fuel delivery to the system. The electric motor is activated when the vehicle's ignition system is turned on and electrical energy energizes the fuel pump. This energy flows through the stator generating a magnetic field. The interaction between this magnetic field and the permanent magnets on the rotor induces a torque that causes the rotor to rotate. As the rotor turns, it transfers motion to the attached impeller via a common shaft, driving the pump's operation [7].

The impeller is responsible for the fuel delivery process by inducing fuel suction and generating the necessary pressure to move the fuel through the system. As the impeller rotates, the blades create a low-pressure region at the inlet of the pump. This low-pressure zone, combined with the higher pressure in the fuel tank, results in a pressure differential that drives the fuel into the pump [8].

Once the fuel enters the pumping chamber, the continuous rotation of the rotor, and thus the impeller, compresses the fuel, increasing its pressure. The pressurized fuel is then directed towards the pump's outlet, from where it is delivered to the fuel injection system, ensuring an efficient and continuous supply of fuel to the engine.

MICROCONTROLLER - The methodology applied to the experiment involved the conduction of a comparative analysis of the results obtained by using different control strategies on the system, applying the P-I-D controller method and the system performance without an implemented electronical controller implemented. The objective was to assess the effect of each test stage on the system behavior, considering control robustness, response time, and pump performance.

The absence of a controller implemented in the system results in an uncontrolled operation limited by the mechanical pressure valve, in which the system variables fluctuate without any control mechanisms to adjust the response. Consequently, these variables run influenced by the inherent variations of the system components. In the experiment, a pressure valve was applied to test this condition and represents a mechanical constraint within the system and was established as a reference condition for subsequent control tests. At this stage, a set of pressure values was recorded as well as the current consumed by the pump.

The initial approach employed to electronically control the system was the implementation of a proportional (P) controller. Equation 1 was implemented in the computer code to execute the P controller and analysis of system behavior, through the resultant response curves, facilitated the fine-tuning of the proportional gain, Kp. At this point, the pressure valve was not considered in the hardware configuration and was disconnected.

The implementation of the integral (I) component into the proportional (P) controller results in the formulation of a proportional-integral (PI) controller, which was the subsequent approach tested during the experiments. The Equation 2 was implemented to the code and 'K' factors were adjusted through fine-tuning its values within the program based on analysis of the system behavior observed in the resultant response curves in an oscilloscope and a serial plotter.

Finally, the last control strategy implemented in the experiment involved the incorporation of a derivative action into the PI controller, resulting in the PID. This mechanism regulates the system output based on three components that perform complementary roles. PID controller mathematically represented in the Equation 3 was incorporated into the logic and the 'K' factors were adjusted through fine-tuning the values based on analysis of the system behavior observed in the resultant response curves in an oscilloscope and serial plotter.

Figure 2 depicts a block diagram of the controller logical implemented in the code utilized during the experiments.

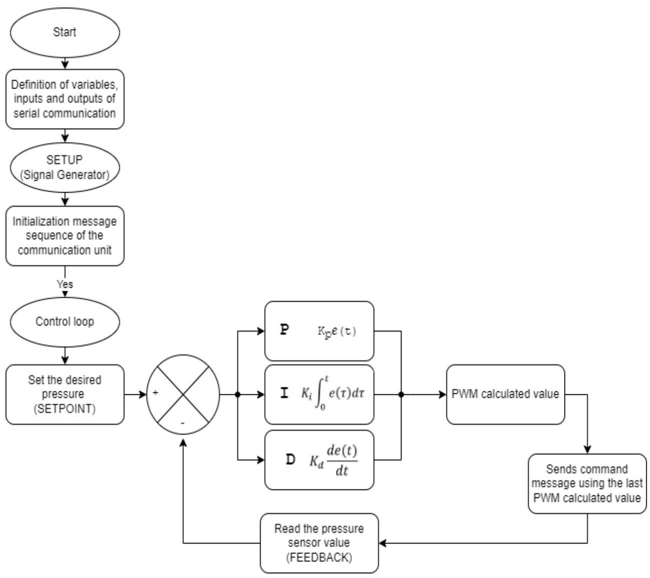

Figure 2. Block diagram of the code developed

RESULTS

The scaled-down model was tested under specified conditions to validate the concepts, and these conditions were compared to identify the scenario that would produce efficient control of the pump.

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SYSTEM MECHANICALLY CONTROLLED - The initial condition tested was the system operation without an electronical controller implemented to set the previous state and get results in original conditions, as depicted at Figure **3**.

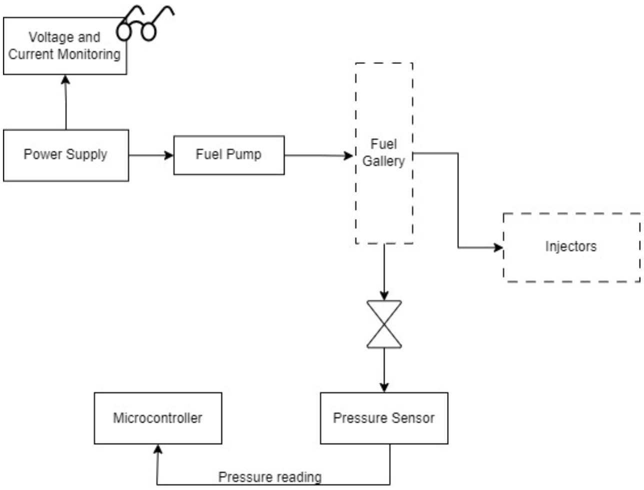

Figure 3. System mechanically controlled

At this phase, different voltage and current ranges were tested, and corresponding pressure values were recorded at each stage. A voltage of 9 volts and a current of 8,27 ampere were set at the power supply and under these conditions, the pump operated at an average pressure of 7,5 bar over a period of approximately 12 seconds and the resulting curve is depicted at Figure 4.

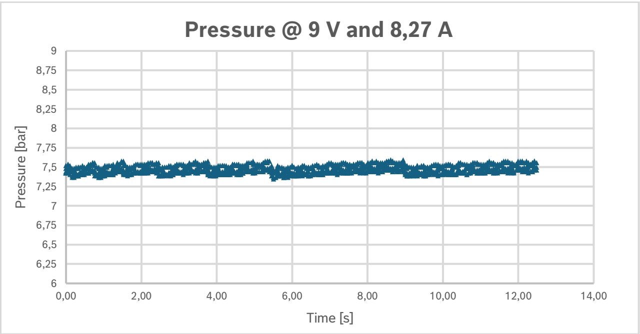

Figure 4. System mechanically controlled

The main objective of this initial approach was to acquire current consumption data in an original condition (not electronically controlled) which would serve as a reference for comparing the current consumption of the electronically controlled pump under different control strategies and the pressure behavior as a baseline.

Based on this, the graph previously presented represent an approximately constant pressure behavior under the applied current and voltage conditions set at the power supply. This was the expected performance, as the setup does not include any control mechanism capable of dynamically adjust the pressure according to operating conditions, with the only influence being mechanical, due to the presence of the pressure regulator valve.

In realistic applications requiring higher pressure values, i.e. applications that require greater load demands, the pump must deliver a larger volume of fuel, which necessitates a higher electrical current. An increase in current consumption directly results in higher load on the alternator, which in turn leads to increased fuel consumption by the engine.

Systems with any control strategies may increase current consumption during operation, as they are designed to function based on the pump's capacity or, when present, the pressure regulating valve.

PROPORTIONAL CONTROLLER - The second scenario tested involved the implementation of a proportional (P) controller to evaluate its effects on the control dynamics and the results obtained concerning pressure variation. It is essential that the controller provides stable operating conditions to ensure most favorable pump functioning. Moreover, the control must be effective in the pressure modulation to reproduce the vehicle behavior in the pump operation.

The P controller was implemented within the program according to Equation 1 and the proportional gain was defined by manually adjusting the gain and its effects in the signal were observed with the use of an oscilloscope and a plotter. Figure **5** depicts the resultant wave of the control system operating with the P controller implemented and *Kp* defined by manually adjustments.

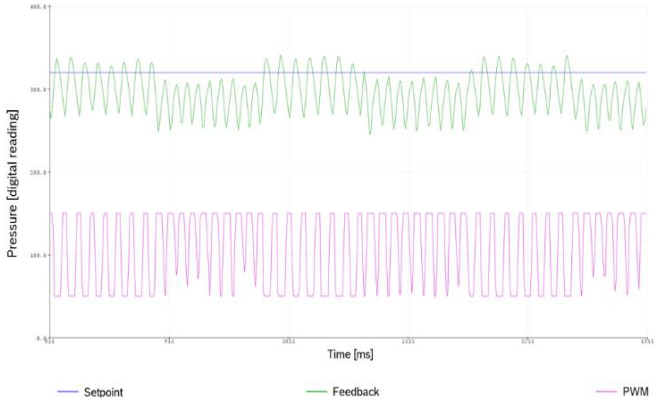

Figure 5. P controller @ Kp = 5.0

It is relevant to mention that the pressure axis (vertical axis) at figure is represented based on the analog reading of the sensor value before conversion to pressure value at bar. At this test, the setpoint was defined as a constant value of 320 (equivalent to approximately 4,6 bar converted).

The associations to the conversions of analog and digital readings, as previously outlined, are defined by the equations depicted at Figure **6** which were implemented in the code developed.

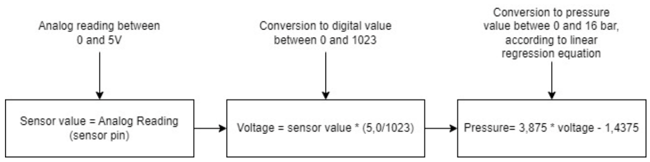

Figure 6. Signal conversions applied

The correlation between the values presented is also relevant for the analysis of the errors observed during the experiments. The sensor's analog reading range covers from 0 to 5V, with each value of this interval being digitally converted into values ranging from 0 to 1023, based on the resolution of the microcontroller used. The analog to digital converter in the microcontroller employs a 10-bit resolution to represent the values, where the smallest increment corresponds to 1 bit. This implies that when the sensor detects voltage values that fall within resolution ranges smaller than 1 bit, these values manifest as inherent errors within the system that can accumulate within the operation and result in the persistent errors observed during experimentation.

PROPORTIONAL – INTEGRAL CONTROLLER - To smooth the system response and consequently the pump operation, an integral action was implemented in the controller. Various combinations of *Kp* and *Ki* were tested and analyzed using an oscilloscope and the serial plotter. The resultant waves from the previously implemented computer code are depicted at Figure **7**, which indicates that, despite the treatments applied within the code, the system response is still not adequately adjusted.

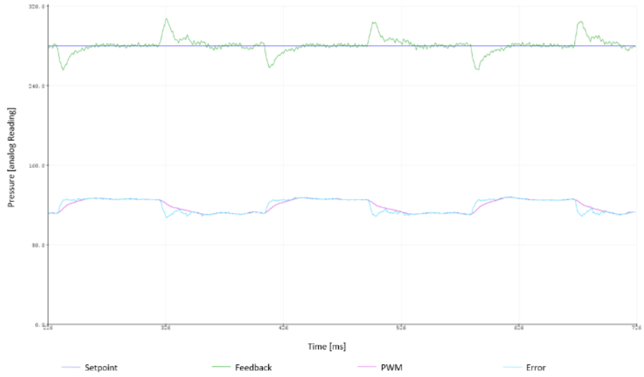

Figure 7. PI controller Kp = 0.05 and Ki =0.1

Under these parameters previously set, a pressure test with a variable setpoint from 200 to 250 (which corresponds to 2,4 to 3,3 bar) was conducted, following a step function to simulate an abrupt pressure change and analyze the system's behavior in terms of stability, responsiveness, and transient response. Figure **8** depicts the resultant curve with the application of a step function and the system electronically controlled by the PI controller.

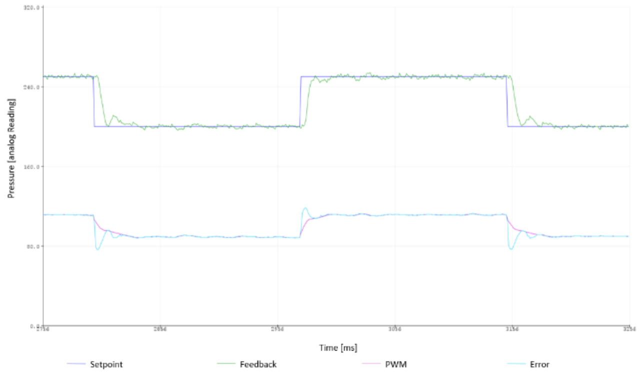

Figure 8. PI controller with step setpoint

From Figure **8**, it can be observed that the pressure response, indicated as the feedback curve, exhibits a delay relative to the setpoint, both during pressure increase and decrease. During the rising phase, the delay indicates a difficulty in the system's ability to reach the required pressure level as defined by the setpoint, and there is some instability at the upper plateau. During the descending phase, the pressure does not reach the setpoint value instantly, showing a necessity for a longer period to stabilize. Additionally, the error curve analysis reveals that during the descent the system has a slow transient response until stabilization is achieved.

Physically, the phenomena previously described indicates that, during operation, the pump may respond more slowly to changes in pressure demand and, consequently, fuel demand. This behavior could be influenced by the system's components. During demand reduction, residual pressure may remain in the injector rail, leading to a slower transient response with potential overshoots until stabilization at the new pressure level. Additionally, the presence of this residual pressure could result in unplanned residual fuel injection, which is undesirable, as it is injected into the system according to the engine's requirements.

Despite the challenges faced during testing, the PI controller demonstrated to be a potencial alternative for implementation in the system. However, additional scenarios with gains adjstments were tested to reproduce operational conditions such as abrupt changes of pressure demand and cyclic variations in pressure levels. At this context, the new conditions were tested by applying a variable setpoint from 3 to 5 bar to analyze the signal and pump behavior under sudden change of pressure demand, and by applying a sinusoidal setpoint variation from 2 to 8 bar to evaluate the controller's periodic response to oscillatory stimuli and to observe the signal's phase shift.

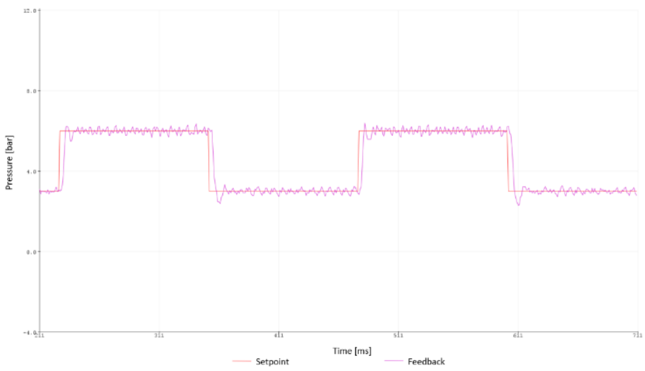

Figure 9. PI with step setpoint @ 3 and 5 bar

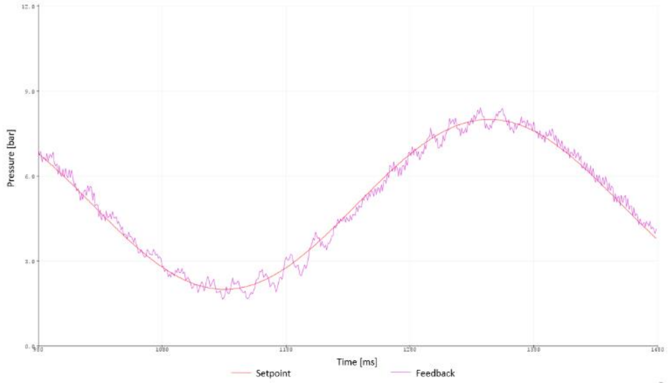

Figure 10. PI with sinusoidal setpoint from @ 2 and 8 bar

By the observation of Figure 9, it can be inferred that the feedback now reaches the setpoint with a shorter delay compared to the previously tested condition, and the same behavior is observed during the signal descent. However, a more pronounced overshoot is observed, indicated by a pressure drop below the setpoint. Additionally, the presence of steady-state error at the plateaus is still evident, which may be originated from the components of the system, such as the injectors.

Figure **10** depicts the generated waveform and does not exhibit any phase shift in the pressure feedback, only showing the interference effects from the system components and, possible indicatives of a necessity of fine-tuning the controller's gains.

In addition to testing the PI controller's output behavior under step and sinusoidal setpoints, the system was also tested with an increasing and subsequent decreasing pressure setpoint, at defined stabilization steps of 2, 3, 4 and 5 bar, simulating diverse fuel demand during pump operation. In this scenario, the previously determined values for the proportional and integral gains were applied, and the resulting waveform is depicted at Figure 11.

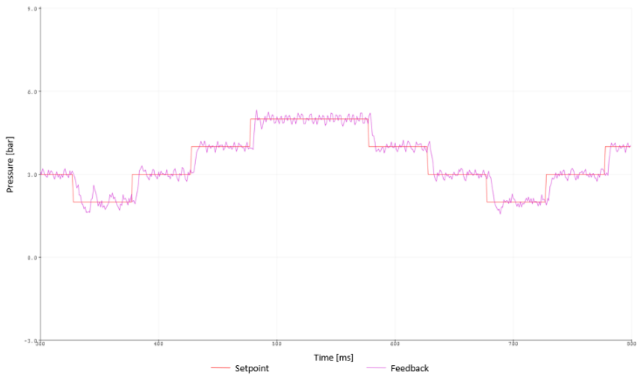

Figure 11. PI controller increasing and decreasing Setpoint

From the observation of Figure **11**, it is possible to identify that the pressure feedback exhibits difficulty stabilizing at the step of 2 bar, showing pronounced undershoot and overshoot, as well as a prolonged descendent time when transitioning from 3 bar to 2 bar. The rise from 2 bar to 3 bar also indicates stabilization difficulties and a longer time to reach the higher setpoint. The other plateaus also present signs of oscillation, overshoot, and undershoot, although less pronounced than those at the lower pressure levels. This feedback curve may suggest interference from the system's hardware components, such as injectors, hose, and connections; and the delays during descent could be attributed to residual pressure in the fuel gallery. Additionally, there's possibly a margin for optimization of *Kp* and *Ki* gains to smooth the response.

PROPORTIONAL – INTEGRAL – DERIVATIVE CONTROLLER - The last control strategy analyzed was the definition of a derivative action into the controller implemented. The effect of the derivative component was tested with a constant defined setpoint of 320, based on analog reading. The effects of the derivative gain didn't represent a significant improvement of the system feedback and signal is depicted at Figure 12.

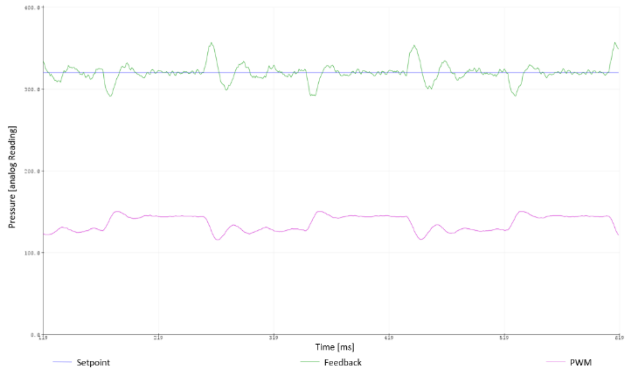

Figure 12. PID controller

CONCLUSION

The experiments were conducted with the objective of validating a control system applied to a single EKP utilizing a signal generator to produce a PWM signal. The developed control system was designed to maintain fuel pressure within the specified limits, with minimal fluctuation, ensuring that the pump delivers the required fuel pressure by dynamically adjusting the PWM duty cycle in response to the engine's operational demands.

Additionally, the validation of the system's efficacy will facilitate the implementation of multi-pump configurations in further studies, where multiple pumps can be balanced to operate in coordination. This balance ensures that an individual pump operates accordingly to the engine demand, improving system performance and fuel delivery efficiency.

After experimentations, it was acknowledged that a reasonable and viable control alternative to be implemented is the proportional-integral (PI) control, as it provides appropriate actions to maintain operation with minimal oscillation within the pressure limits defined by the setpoint. The system exhibited some overshoot and the experiments still indicated certain challenges in the transient response and presence of steady-state error. More precise adjustment of the gains, involving the application of mathematical methods such as the Ziegler-Nichols tuning, for both the proportional and integral actions, could provide the system with more stable responses during operation.

The experiment confirms that a pump control can succeeded through dynamic adjustment of the PWM, when compared with conventional system with any control strategy. In an application involving *n* pumps, the implementation of a PI controller can also be adopted, by modulating the individual pump actuation based on the engine's requirements through PWM duty cycle adjustments. An individual operating limit can be set to prevent overloading, and the pumps can be activated as needed.

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