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Original Research Article

Relay Based Auto Tuner for Calibration of SCR Pump Controller Parameters in Diesel after Treatment Systems

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Abstract

In this paper, the application of relay-based auto tuning method for calibration of PID parameters of SCR (Selective Catalytic Reduction) pump pressure controller in a diesel engine is described. SCR pump, which is defined as the plant of the system in this study, provides urea for pressure line in the SCR urea dosing system. The pump is actuated by a BLDC (brushless DC) motor and the motor adjusts the pump frequency. As a result, the speed of the motor is controlled by PWM signal which is determined by PID controller.

Auto tuner was designed to bypass the actual SCR pump controller with relay signal which introduces an oscillation to the system. Based on the relay and plant output signals, system identification is finalized as a first order system with dead time. Once the model is identified, different tuning algorithms such as Ziegler-Nichols, Tyreus Luyben, Ciancone-Marlin and Internal Mode Control become available for comparison. The best algorithm, based on comparison results, can be selected by users. In this study, Ziegler- Nichols method is chosen based on the system performance.

Key Words: PID controller, auto–tuning, relay method, SCR pump

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1. Introduction

In automotive systems, PID controllers are prevalent for actuator position control such as EGR, throttle or swirl valves and vehicle system functions such as idle speed controller or SCR pump controller because they have simple structure to build, provide robustness against the deviation of system output from the reference signal and disturbance rejection.

Due to tightening emission standards, components of diesel engines and after treatment systems have been becoming complicated. As a consequence, time, effort and complexity in control of these components have been increasing with each passing day in order to meet the strict emission standards, engine performance targets, and driver expectations. Insufficient control of PID parameters might lead inadmissible drivability issues, mechanical hardware damages and emission results in terms of NOx, smoke, etc. Therefore, calibration of PID gains has a significant importance in automotive system control.

PID controller tuning means computing the proportional, integral and derivative parameters in a way to meet the desired performance specification in steady state and transient operations under different conditions such as set point change, disturbance, load demand change as well as compensating the effects of using new or aged components.

Since most of the actuators, used on air path or after treatment components, are controlled by means of PID controllers, different techniques have been developed for the tuning of PID parameters. Some of these methods are based on trial and error process which results in excessive time consuming. Therefore, they require an experienced person for the calibration process. Furthermore, these methods might cause physical damage if they are used on such a hardware, whereas relay-based auto tuning avoids trial and error, and minimizes the possibility of operating plant close to the stability thresholds. Whereas conventional methods for PID controller tuning lead a subjective and heuristic process based on the existing knowledge and experience of the system and skills of calibration engineer; relay based tuning is simple to generate and maintain a controlled oscillation. So, it is very efficient in determination of the system parameters such as critical gain and critical frequency. The simplicity of system identification and calibration process is the main motivation in this paper.

2. The Theory behind Auto Tuning Method

In relay auto-tuning application, a relay element is placed in parallel to the PID controller. The relay takes over the control by a switch in closed-loop system with the plant in order to obtain limit cycle oscillation. In this way the controller gains are estimated automatically by implementing relay action in negative feedback.

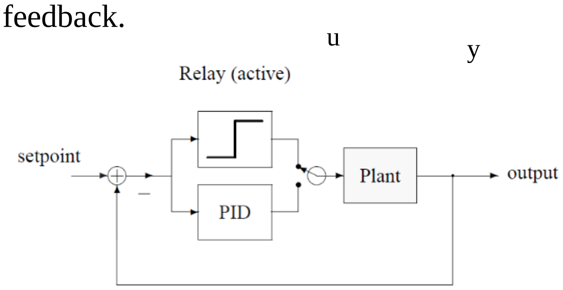

Figure 1. Relay auto tuning process

In a system as shown in Figure 1, the DC gain, K_{dc} is equal to the ratio of the system output to the input:

$$K_{dc} = \frac{\Delta y}{\Delta u} \quad (1)$$

Once the operating point reaches to steady state, the first step change is applied to the system as an input. The amplitude of the output signal of the system is controlled by setting the amplitude of the input signal. This gives us an advantage to identify system parameters such as ultimate gain and period.

The calculation of the critical system parameters is based on zero-crossing detection algorithm. The system output changes with a dead time after the first step change is applied as relay output.

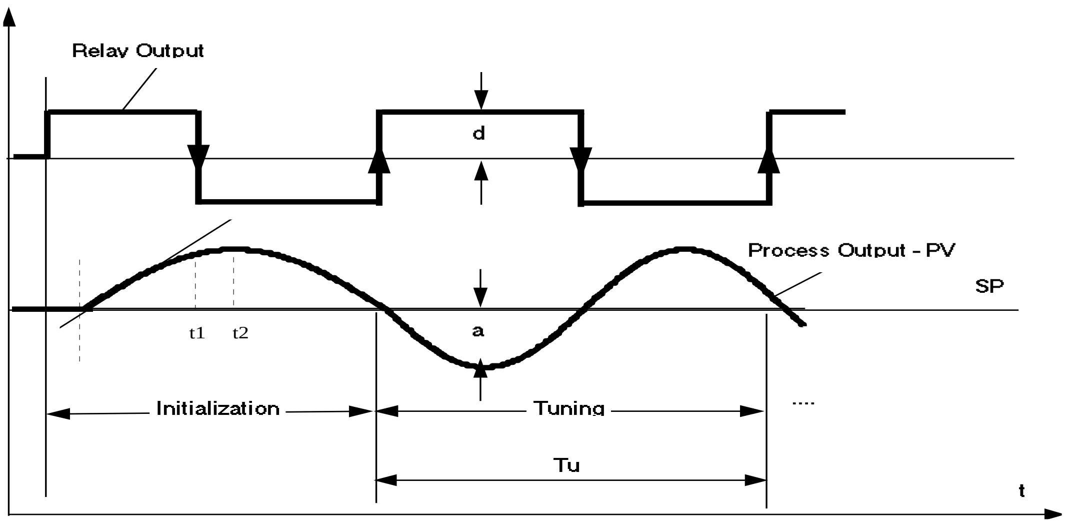

Figure 2: Output signals of the relay and the system

In figure relay signal which steps in the opposite direction is subsequent to first system output. As a result of that, the system output moves in the opposite direction after dead time as well. This means that the loop is under two state control. Each time when the system output crosses the set point the relay is switched for a few periods. Relay signal causes the system output to oscillate at system ultimate period and gain. Here, T_u refers to ultimate period, whereas K_u is the ultimate gain. Ultimate gain can be described as the ratio of the relay amplitude to system oscillations.

$$K_{dc} = \frac{1}{G(j\omega)} = \frac{4d}{\pi a} \qquad (2)$$

$$T_u = \frac{2\pi}{\omega} \qquad (3)$$

with ω: critical frequency

In this system, dead time can be determined the time between the first switching of the relay in the opposite direction and the time at which the system output reaches the maximum in a first order model with a dead time [3]. The time lag and delay can be calculated after obtaining the ultimate values and dc gain:

Time lag, T:

$$\frac{K_{dc}}{\sqrt{1+(\omega_u T)^2}} = \frac{1}{K_u} \longrightarrow T = \frac{1}{\omega_u}\sqrt{(K_{dc}K_u)^2 - 1} \qquad (4)$$

Delay, τ:

$$\tau = \frac{1}{\omega_u}\left(\pi - \tan^{-1}(\omega_u T)\right) \qquad (5)$$

At this point, a great variety of tuning rules can be used to calculate the parameters of a PID controller.

2.1. PID tuning methods

The following PID tuning methods are the scopes of this paper:

Ziegler Nichols Method:

The trial and error tuning method based on sustained oscillations is one of the most known and popular method for PID tuning. By using Table 1 it is possible to calculate PID gains after obtaining critical system parameters.

Table 1. Controller parameters for Ziegler Nichols Method

Controller	K_c	T_i	T_d
P	$0.5K_u$		
PI	$0.45K_u$	$T_u/1.2$	
PID	$0.6K_u$	$0.5T_u$	$T_u/8$

Refined Ziegler Nichols Method:

This more conservative method is usually preferred when the large overshoots are undesirable. The settings are as shown in Table 2.

Table 2. Controller parameters for Refined Ziegler Nichols Method

Controller	K_c	T_i	T_d
PID / some overshoot	$0.33K_u$	$T_u/2$	$T_u/3$
PID / no overshoot	$0.2K_u$	$T_u/2$	$T_u/3$

Tyreus Luyben Method:
Although the calculation of PID parameters is based on critical gain and period as in Ziegler Nichols Method the way is different. The parameter settings for PI and PID controllers are summarized in Table 3.

Table 3. Controller parameters for Tyreus Luyben Method

Controller	**K_c**	**T_i**	**T_d**
PI	K_u /3.2	2.2T_u	-
PID	K_u /3.2	2.2T_u	T_u/6.3

Ciancone Marlin Method:
On the purpose of obtaining the PID parameters, this method uses some graphs to meet the control target which is minimizing integral of the absolute value of the error (IAE) considering +/- 25% change in the process model parameters and limits on the variation of the manipulated variable. The method provides the controller parameters based on a dynamic model which is a first order plus dead time model as explained in [4].
Internal Model Control:
This method gives two advantages. First, it takes into account model uncertainty and second allows the designer to trade off control system performance against robustness to process changes and modelling errors.

3. Experimental Setup

In this application, the system identification and parameter estimation is handled on a urea dosing module of SCR catalyst for a heavy duty diesel after treatment system. As shown in figure 3, the urea is pumped into the pressure line from the urea tank. The pressure sensor in the pressure line is used for feedback control. According to the error between actual pressure and set point, the controller generates the appropriate PWM signal in order to control the speed of the BLDC motor. The motor connects to the pump and adjusts the pump frequency. After the pressure stays in steady state, the pumped urea mass equates to the return flow through the throttle based on the mass balance. Urea is injected into the exhaust pipe when the injection command is sent to the injector by the urea Dosing Control Unit (DCU).

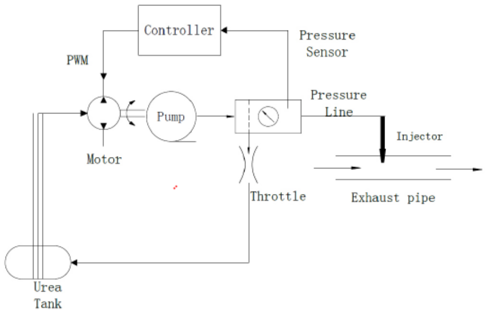

Figure 3. Urea dosing system

Calibration software INCA is used as an interface between Auto Tuner and DCU.

4. Auto Tuning Procedure

Auto-Tuner, which is a MATLAB based, fast and reliable calibration tool, has been initially designed by AVL UK, later further developed by AVL TR. The tool has the ability to work online in connection with a calibration software.
Auto-tuner bypasses the actual ECU controller with relay signal which introduces an oscillation to the system. Based on the relay and plant output signal, system is identified as a first order system with dead time as mentioned in previous sections. Once the model is identified, four different tuning algorithms would be available to compare and find out the best response.

4.1. Parameter configuration

In order to provide the tool to deactivate the PID controller by setting the gains of the controller to zero and activate relay, the required ECU parameters should be configured according to SCR pump pressure control algorithm shown in figure 4.
Since the adjustment of controller output can be done by just altering Duty_max & Duty_min together at the same time to the same duty cycle, configuration of parameters can easily be accomplished as shown below in figure 4.

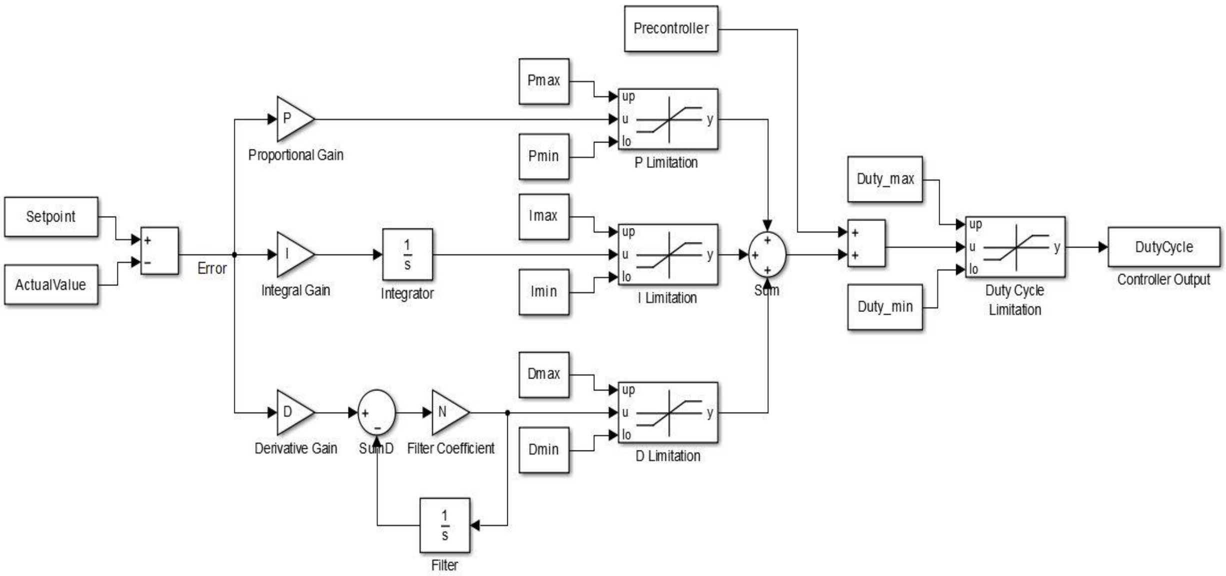

Figure 4. SCR pump pressure control algorithm

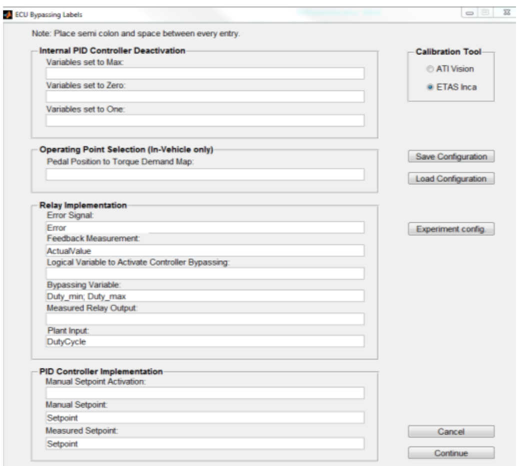

Figure 5. Auto Tuner interface to define the by passing parameters

4.2. System identification

The GUI is designed in user-friendly way so that the next step in the tuning process is restricted by a single button by deactivating the others.

In this part, ECU PID would be bypassed by the relay block to actuate the system with the necessary input required by the system identification. Based on the measurements, DC gain of the first order system with delay is identified as represented in figure 6.

Then, according to amplitude and hysteresis of relay signal, critical gain and frequency are estimated as listed in figure 7.

4.3. PID tuning rules

- By using five parameters (DC gain, critical frequency, critical gain, time lag and time delay), it is possible to get sets of PID values based on Ziegler-Nichols, Tyreus-Luyben, Ciancone-Marlin and Internal Mode Control.
- Also, calculation of parameters can be configured according to supplier specific PID tables.
- Tool can calculate each controller and save for later comparison.

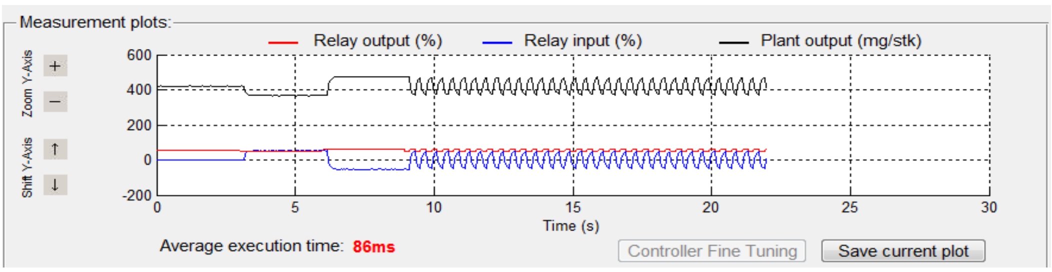

Figure 6. Auto Tuner interface for system identification and parameter estimation

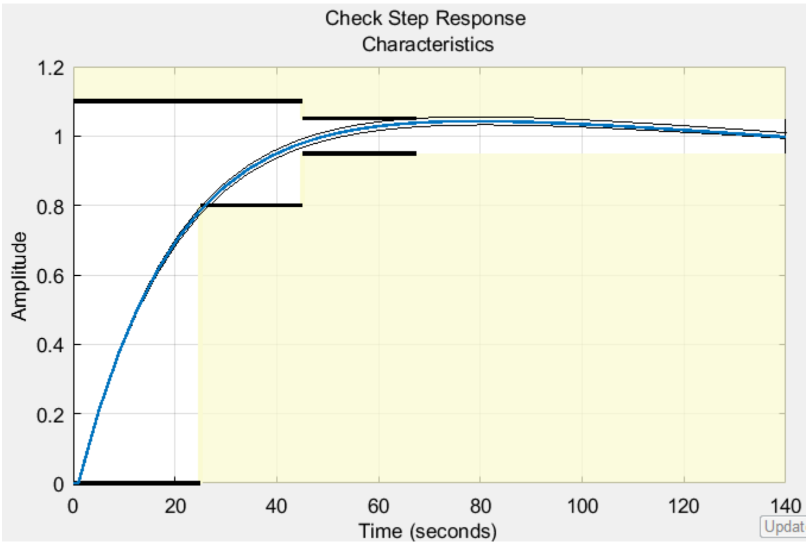

Figure 8. Controller performance with different types of tuning method

	N (rpm)	TQ (Nm)	K_{crit}	f_{crit} (Hz)	K_{dc}	P_{coeff}	I_{coeff}	D_{coeff}	Method	Controller
3	1500	100	0.194	2.4732	7.6076	0.06109	0.5421	0	Refined Ziegler-...	PI (Kp, Ki)
4	1500	100	0.194	2.4732	7.6076	0.060626	0.067474	0	Tyreus-Luyben	PI (Kp, Ki)
5	1500	100	0.194	2.4732	7.6076	0.058789	0.58159	0	Ciancone-Marlin	PI (Kp, Ki)
6	1500	100	0.194	2.4732	7.6076	0.019578	0.28028	0	Internal Model C...	PI (Kp, Ki)

Figure 7. Auto Tuner interface to show the results for different tuning methods

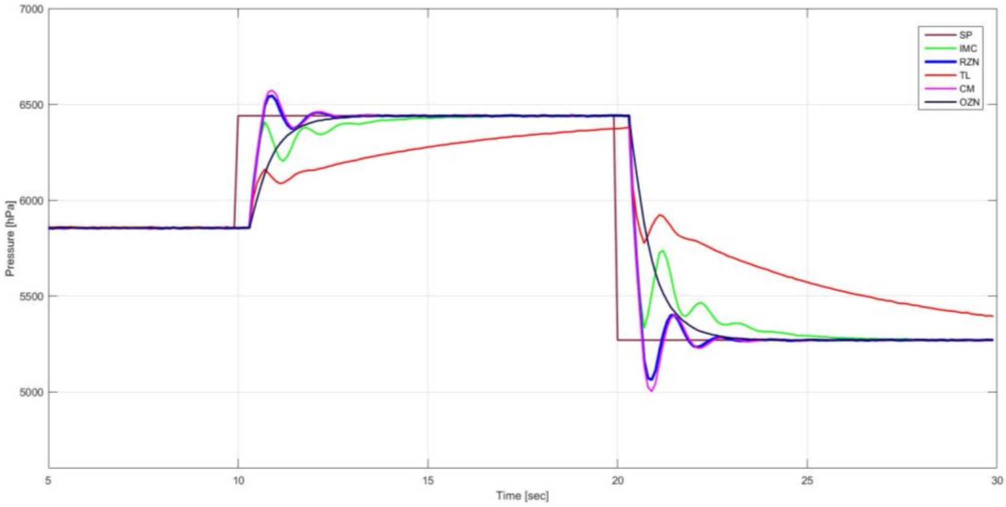

Figure 9. Response Optimization for further improvement

- In figure 8, based on the comparison result of system performance criteria between abovementioned PID tuning methods, the first PID gains are set.
- As a next step, if it is required, Response Optimization Toolbox in Simulink can be used as demonstrated in figure 9, for further improvements in PID gains by using initial values which are estimated in previous steps and specifying step response characteristics via Auto Tuner GUI.5.

4.4. Validation Results

According to the comparison result between different tuning methods, Ziegler Nichols tuning method is decided to use in the current application, since it gives the most satisfactory performance in terms of rise time, overshoot and steady state error when considering the SCR pump system requirement. Figure 10 and Figure 11 show the final system performance in case of different step changes.

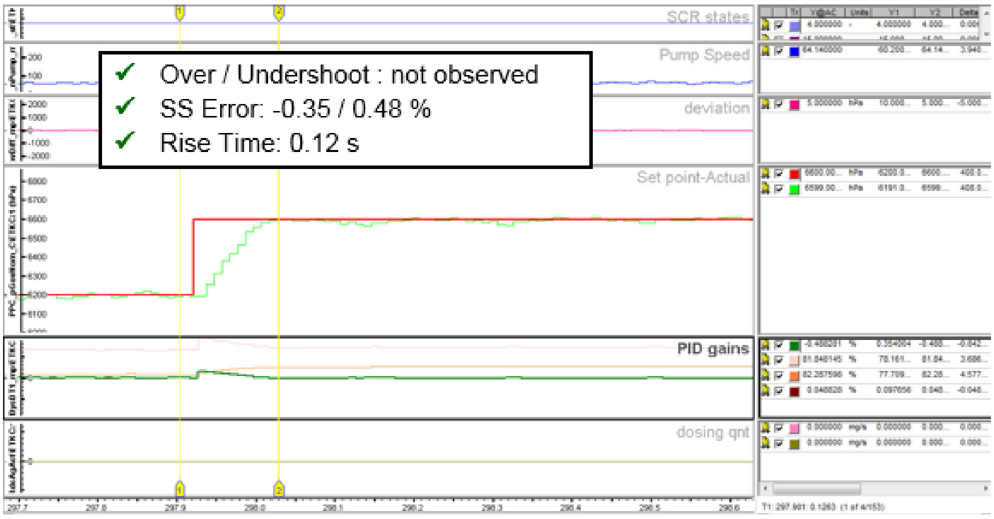

Figure 10. Dosing Pump pressure set point step change (6200hpa to 6600hpa)

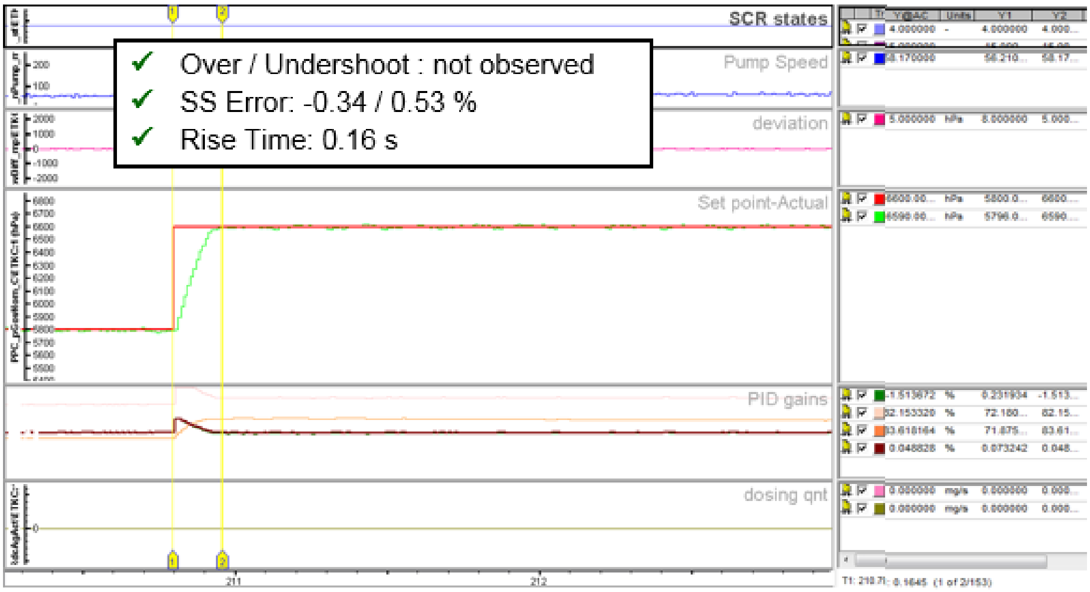

Figure 11. Dosing Pump pressure setpoint step change (5800hpa to 6600hpa)

5. Conclusion

Along with the demonstration of relay based PID auto tuning for the automated calibration of the SCR pump controller on a heavy duty diesel engine after treatment system, a MATLAB based GUI is used to estimate the critical parameters and PID gains by online connection to the electronic control unit via a calibration software tool.

According to validation results for different step changes, it can truly be said that the performance criteria such as rise time, steady state error, amount of overshoot/undershoot are within acceptable limits when the PID parameters are calculated by using relay based Auto Tuner.

This research explains that applying manual PID tuning is time consuming since it is based on trial and error to search for the ultimate gain, whereas auto tuner avoids trial and error as well as operating near the instability limit. Besides, auto tuner provides simplicity to automate the procedure even if the designer does not have enough experience.

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