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LIISA LAHTI
PERFORMANCE INDEX FOR CLOSED-LOOP CONTROLS

Master’s Thesis

Tarkastaja: professori Risto Ritala
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ABSTRACT

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Control performance assessment is becoming increasingly important, as processes are wanted to be as efficient as possible. Performance assessment measures can indicate how well the controllers are functioning, and what can be done to improve their performance. They can be used as an aid in tuning the controller, as well as to monitor the control performance during process operation.

The aim of this thesis is to present methods developed for control performance assessment, and evaluate the usability of these methods in assessing the performance of marine engine controls. After presenting the theory, a method to assess the engine control performance is developed. The factors needed to be taken into account regarding the specific processes are discussed. The developed algorithms are then evaluated first with a basic process model and PID control function. Once the functionality is tested, the methods are evaluated with an engine model. Finally, the performance assessment methods are evaluated on an actual engine. Their usability and limitations are discussed, and further actions to be taken are presented.

This thesis provides an overview on the present performance assessment methods available, discusses their practical implementation, and their usefulness in marine engine control performance evaluation. However, it is only a start to developing a functioning engine control performance assessment tool. Further developing is still needed. More tests on the actual engine process controls need to be done, to verify the functionality of the methods in different situations. Also, a simplified result from the performance assessment tool should be provided to have one clear value to indicate the whole engine control performance.

TIIVISTELMÄ

LIISA LAHTI: Suljettujen säätimien suorituskykyindeksi
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Kiinnostus säätimen suorituskyvyn mittaamistyökaluja kohtaan kasvaa jatkuvasti. Syynä tähän on halu prosessin tehokkuuden kasvattamiseen, ja resurssien optimaaliseen käyttöön. Prosessin säätötulos vaikuttaa suoraan koko prosessin tehokkuuteen ja prosessista saatavan lopputuotteen laatuun. Tämän vuoksi säädön suorituskyvyn mittaaminen tuo arvokasta tietoa siitä, miten prosessin toimintaa voidaan parantaa.

Tämä diplomityö käsittelee säädön suorituskyvyn mittaamiseen kehitettyjä menetelmiä, ja niiden hyödyntämistä käytännössä mittamaan laivan moottorin säätöjärjestelmän suorituskykyä. Tutkimusosa käsittelee säädön suorituskyvyn mittamiseen kehitettyjä menetelmiä, ja teoriaa niiden takana. Menetelmien soveltuvuutta laivan moottorin säätäjörjestelmän suorituskyvyn mittaamiseen on myös arvoitu, ja prosessin ominaisuuksia on käsitelty lyhyesti.

Tiedonhaun pohjalta on implementoitu algoritmi, joka mittaa säätimien suorituskykyä eri tilanteissa. Tätä algoritmia on testattu sekä yksinkertaisella prosessimallilla, että moottorimallilla. Lopuksi metodien toimivuus käytännössä, oikean moottorin säätimien suorituskyvyn mittaamisessa on myös arvioitu.

Diplomityön antaa pohjan suorituskykymittaustyökalun kehittämiseksi. Kehitettyjä indeksejä ei kuitenkaan voida vielä implementoida käytäntöön. Lisää testejä tulee tehdä eri moottorin sisäisten prosessien säätimien suorituskyvyn mittaamisesta, jotta varmistutaan siitä, että indeksit toimivat halutusti. Lisäksi indeksien yhdistämistä tulisi harkita. Näin voitaisiin yhdellä arvolla ilmaista säätimien suorituskyvyn hyvyys, eikä indeksien tulkitsemiseen kuluisi liikaa aikaa.

PREFACE

This thesis was done for Wärtsilä engine performance and control department. The thesis process was started in November 2017, and final tests were done in April 2018. During this process, many people at the department have helped me and I want to thank them for that. In particular, I want to thank my mentor, Jani Yli-Kätkä, who has been giving me advice and aided me throughout the process. I also want to thank Sören Hedvik for making it possible for me to do my thesis at Wärtsilä.

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In Vaasa, 24.4.2018

Liisa Lahti

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LIST OF SYMBOLS AND ABBREVIATIONS

API	Absolute Performance Index
CPU	Central Processing Unit
DNV GL	Maritime classification society
DF	Dual fuel
et al.	Latin et alii or et alieae, and others
FCOR	Filtering and Correlation analysis
GMV	Generalized Minimum Variance
GS	Gain Scheduling
IAE	Integral of Absolute Error
ISE	Integral of Squared Error
ITAE	Integral of the Time weighted Absolute Error
ITSE	Integral of the Time weighted Squared Error
LQG	Linear Quadratic Gaussian
MIMO	Multiple-Input, Multiple-Output
MPC	Model-Predictive Control
MVC	Minimum Variance Control
MV	Minimum Variance
PID	Proportional-Integral-Derivative controller
PI	Proportional-Integral controller
RI	Robustness Index
rpm	revolutions per minute
SISO	Single-Input, Single-Output
WSDE	Wärtsilä Simulink Development Environment

a	Acceptable oscillation amplitude
$A(z^{-1})$,$B(z^{-1})$,$C(z^{-1})$, $G(z^{-1})$, $F(z^{-1})$	Polynomials
$\boldsymbol{\alpha}$	Vector of autoregressive parameters
$\widehat{\alpha}$	Autoregressive parameter
d	Process delay
δ	Settling limit
$\Delta u\Delta y$	Correlation between control and measurement signal increments
e, E	Error
$E\{.\|.\}$	Expectation operator
e_{ss}	Steady-state error
G_{pro}	Process transfer function
γ	Recursive calculation parameter

h	Application sample time
IAE	Calculated IAE
IAE_d	Dimensionless IAE index
IAE_{lim}	IAE value limit
I	Minimum variance index
I_i	Idle index
J, V	Cost function
K_d	PID controller, derivative gain
K_i	PID controller, integral gain
K_p	PID controller, proportional gain
$load$	Load disturbance occurrence indicator
m	Autoregressive model length
n_{lim}	Limit of acceptable load disturbances
n_y, n_w	ARMA model order
η	Normalized minimum variance index
$\eta_{MV,cor}$	Minimum variance performance index for FCOR
θ_a	Net effect of time delays
r_0	Step change magnitude
r_{yw}	FCOR parameter
s	Continuous Laplace operator
s	Idle index parameter used in on-line calculation
t	Time
T_i	PID Integral time constant
t_{neg}	Negative correlation between measurement and control signal increments
t_p	Peak response
t_{pos}	Positive correlation between measurement and control signal increments
t_{r1}	Rise time, overdamped system
t_r	Rise time, underdamped system
T_s	Dimensionless settling time
t_s	Settling time
T_{sup}	Supervision time
T_u	Ultimate period of the process
σ^2	Variance
σ_w^2	Variance of estimated noise
σ_{MV}^2	Estimated minimum variance benchmark
σ_y^2	Current output variance
u, U	Control signal
w	Noise signal

ω_u	Process ultimate frequency
ω_i	Integral time constant based parameter
x	Load disturbance sum
$\boldsymbol{X}$	Matrix containing output values
y, Y	Process output
$\bar{y}$	Mean of the process output
$\boldsymbol{y}$	Vector containing output values
ψ_i	Impulse response coefficients of the disturbance
z^{-1}	The discrete backward shift operator
Λ	Forgetting factor
$\boldsymbol{\Lambda}$	Diagonal matrix of the forgetting factor

1. INTRODUCTION

Process control performance assessment has become increasingly important, as efficiency and resource optimization have become some of the main objectives in every system. It is no longer enough to have a “good” controller. The controllers need to be optimized to produce the desired result with accuracy and speed, without compromising the end product quality.

The increasing need to improve controller performance has led to the development of many control performance assessment techniques. The methods have been researched and discussed by Jämsä-Jounela et al. (2003), Jelali (2006; 2012), Visioli (2006), Ordys et al. (2007) and Huang and Shah (1999), among many others. The control performance methods assess the performance of the controller, and indicate whether or not the control performance reaches the requirements. Furthermore, some of the measures also suggest the reason behind poor control performance, and thus make it easier to improve the control result.

The aim of this thesis is to research the techniques developed for control performance assessment, and determine how they can be utilized to assess the performance of the closed-loop controllers in marine engines. The scope is limited to the processes controlled with a PID (Proportional-Integral-Derivative) controller, as they are the most popular engine controllers. Based on the research, a method to measure the performance of the control loops is established. Additionally, the performance index as an aid in tuning the control parameters is explored, and the performance requirements for the process are discussed. Finally, the performance index is validated on the engine. The amount of CPU (Central Processing Unit) power it takes to calculate the indices is also evaluated.

The marine engine control system consists of multiple control loops that work together to produce power for the vessel. The efficiency of the engine greatly depends on how well the controllers function. At the moment, there is no dedicated method to assess the control system performance. The engine controls are usually tuned based on the operators’ intuition and knowledge, but no definite indicator of tuning quality is provided. Due to this, the controls may not be working as well as they could. In many cases they are only tuned to be “good” enough.

Before researching and developing the control index, it is important to know the system specific requirements for the control performance. The engine control system consists of multiple control-loops that all have their own dynamic behaviour, and control performance requirements. The developed index should be able to assess the performance of all these, independent of the process.

For many of the engine controls, the aim is to regulate a reference value, and large deviations from reference are unwanted. However, in some cases, the controllers are also required to make a rapid transition from one value to another. Some controllers are more critical to the overall system performance than others, and thus their control performance has more strict requirements.

The area of control performance assessment is widely researched, and many methods have been developed in literature. Because the PID controllers are the most popular control type in the industry, many of the studies focus on their performance assessment. Alexandrov and Palenov (2014), and Yu et al. (2001), among others emphasize the fact that PID controllers are often poorly tuned, with a lot of room for improvement. Thus, performance assessment is clearly needed in the industrial control applications. Many processes would benefit from having a distinct performance index. Using it actions can be taken to keep the controller performance close to optimal.

When implementing the control performance measures in practice, the usability, and ease of interpreting the values are important design criteria. It may not be beneficial to calculate a complex index value, if its interpretation is not straightforward. It is more valuable to have a few simpler indices that are easily understood. This way the performance assessment will be less time consuming. In addition, a simple index value needs less calculation power, and is more easily adaptable to different processes.

The structure of this thesis is as follows. The closed-loop control theory is presented in the Chapter 2, which discusses the basic principles of the control strategy, and in particular the PID controller. The common methods to tune the PID controllers are also presented. Additionally, the feed-forward control and adaptive PID control are discussed.

Chapter 3 focuses on the motivation behind developing a performance index, both in general and from the engine control point of view. The requirements specific for engine controls are discussed. Some important closed-loop controllers are studied in more detail.

Chapter 4 presents the main existing results on performance indices. First the reasons causing poor control performance are provided, and then the existing performance assessment methods are overviewed. The selection of a performance index is discussed. Some of the most common indices are discussed in more detail. Their mathematical theory and suitability to assess control performance depending on system states is presented.

Chapter 5 presents the implementation of the indices based on the theory in Chapter 4. First, the indices chosen for engine control performance assessment are discussed. Then, the test system is presented, after which the index implementation is discussed in detail. Lastly, the functionality is tested using a simple process model and PID controller.

The index functionality is tested with a Simulink model of the engine process, and on the actual engine. The results are presented and analysed in Chapter 6. The testing focuses in validating the chosen indices with actual process models and values: i.e. that they provide relevant information about the engine control performance. The index calculation is implemented to two of the engine control loops. Their performance is assessed during different operation states. The indices as an aid in tuning the engine parameters is evaluated.

Chapter 7 focuses on the future development of the performance index. Suggestions are given on improving the developed algorithms and benefits to the end user. Conclusions are made in Chapter 8.

2. THEORETHICAL BACKGROUND

According to Åström and Hägglund (2001) the controller in the closed-loop structure is most often the PID controller. Furthermore, Guzmán and Hägglund (2011) state that the PID controller is often implemented together with a feed-forward controller in order to achieve better control performance. There is also a growing interest in using adaptive PID control. Liu and Daley (2001) accredit this to adaptive PID controls being better able to cope with processes where the dynamic behaviour does not stay consistent.

This chapter first explains the basic closed-loop control structure. After this, the structure of the PID controller is introduced, and good practices to tune the controller are presented. The feed-forward and adaptive control principles are discussed briefly.

2.1 Closed-loop control

The closed-loop structure is the base of controllers. It is presented in Figure 1. The main characteristic of the closed loop controller is that it takes a feedback signal from the process output, and compares it to the reference signal (Dorf 1989).

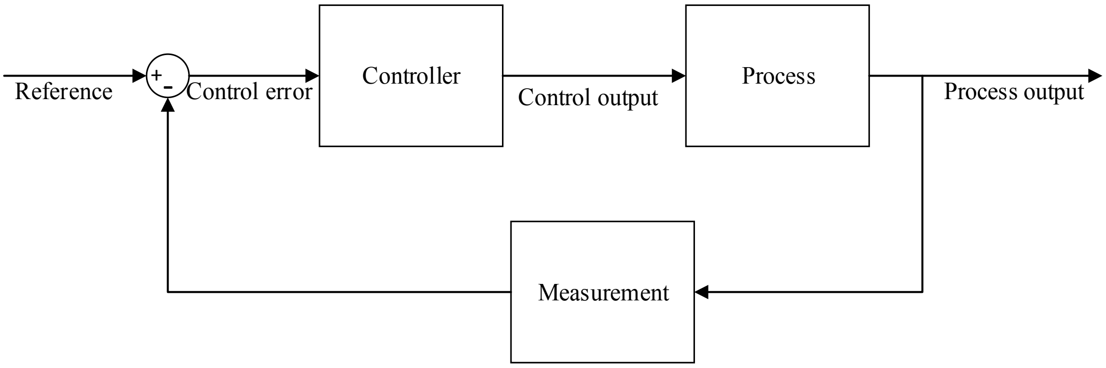

Figure 1. *A basic closed-loop control structure. Adapted from (Dorf 1989, p. 3)*

The closed-loop control structure consists of a controller, process and a measurement, as seen in Figure 1. The reference signal is fed into the loop, and the measured output value is subtracted from it. The resulting error signal is fed to the controller, which, depending on the controller type, performs different calculations in order to provide a controller output that reduces the future control error. The output from the controller is fed to the process. The resulting output from the process is measured and fed back to the loop.

According to Dorf (1989, p. 115-116) closed-loop control has many advantages. Firstly, the system is more capable of handling the variations in process parameters. Secondly, the transient response of the system is more easily controlled and adjusted when using a feedback control strategy. Furthermore, most systems include disturbances and noise, which are more easily rejected by implementing a closed-loop strategy. Lastly, the steady-state error is easier to reduce when using a closed-loop structure.

However, Dorf (1989, p. 115-116) also points out, that there are drawbacks and costs related to closed-loop control. Firstly, the additional components and complexity of the system increase the costs when comparing to an open-loop control strategy with no feedback signal. Adding a sensor to the feedback part also increases noise and makes the system less accurate. Finally, the stability of the open loop system does not always indicate that the closed-loop system is stable as well, and thus the stability of the closed-loop system must be examined.

2.1.1 PID control

The Proportional-Integral-Derivative controllers are widely used in industrial settings (Ang et al. 2005; Yu et al. 2011). The PID controller is implemented in the closed control loop depicted in Figure 1, and it uses the control error signal as its input. The basic PID structure is given by (Åström & Murray 2009, p. 293)

$$u = K_p e + K_i \int_0^t e(\tau)d\tau + K_d \frac{de}{dt}, \tag{1}$$

where the control output is u, the control error signal is e, and the PID controller gains are K_p, K_i and K_d.

When Laplace transforming (1), the control output reads as

$$U(s) = K_p E(s) + \frac{K_i}{s} E(s) + K_d s E(s), \tag{2}$$

where s is the Laplace variable (Ellis 2012). The basic structure of a PID controller in a closed-loop is shown in Figure 2.

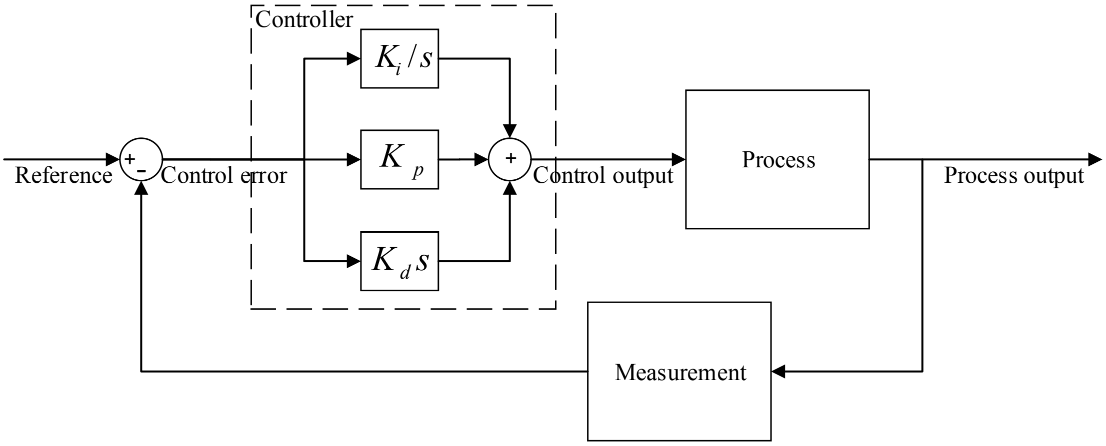

Figure 2. *A basic closed-loop structure with a PID controller. Adapted from (Dorf 1989, p. 3; Åström & Murray 2009, p. 294)*

The Equations (1) and (2), and Figure 2, are only one way to implement the PID function. There are other structures as well, but all of them are based on the same principles. Furthermore, as Åström and Murray (2009, p.294) state, the presented structure is an idealized representation of the PID controller, and to get the actual controller that can be utilized in practice, it needs to be modified. According to Ang et al. (2005), in the actual implementation of the PID controller the D-input must be filtered, and the integrator must have an anti-windup method. To implement the controller digitally, it needs to be discretized (Åström & Murray 2009, p. 311).

According to Ang et al. (2005), each of the terms in the PID controller have their own purpose, and modifying their gains affects the dynamics of the closed-loop system. The proportional term is responsible for the overall control action, which is proportional to the error signal, and the integral term works to reduce the steady-state error. The main function of the derivate term is to improve the transient response.

One of the major advantages in using the PID controller is its simple structure (Zhao et al. 2012). For this reason, the controller is widely used, and can be applied to many control situations (Ang et al. 2005). However, the simple structure is also an important contributor as to why the performance of the system is often not optimal (Zhao et al. 2012). Furthermore, the PID controller tuning is often done incorrectly, which may result in too slow or too aggressive control response, or even cause safety problems (Yu et al. 2011).

The structure of the PID controller can be modified by setting one or more of the gains to zero (Lewis & Yang 1997). A common way is to implement just the integral and proportional terms of the controller and leave the derivative term out. This forms a PI –controller. Other implementations such as a P, or PD controller can also be used depending on the controller requirements.

When designing a PID controller for industrial applications, many factors need to be considered. According to Liu and Daley (2001), these include nonlinearities, external disturbances, and equipment wear and ageing. They also state that the time for tuning is often limited, and often the resulting PID parameters are based on subjective measures.

Because the PID controller is so widely utilized, measuring its performance is the main topic of this thesis. By measuring the control performance, it is easy to evaluate how well the controller is tuned. With this knowledge, actions can be taken to further improve the PID performance. However, the basic PID function is not always sufficient, and the feedforward action or the more advanced, adaptive PID needs to be implemented.

2.1.2 PID tuning

Many tuning methods have been developed to achieve good PID control performance. Examples of tuning methods are given by Liu and Daley (2001). They mention the Ziegler-Nichols rule, and its modifications, and minimizing the IAE (Integral of Absolute Error) or the ITSE (Integral of the Time weighted Squared Error). These tuning methods offer a simple algorithm to find out good PID controller parameters.

However, the aforementioned methods do not always provide the best tuning result from the application perspective. Because of their simplicity, they do not take into account the entire dynamics of the process. Åström and Hägglund (2001) mention that many of the PID controllers are tuned using the Ziegler-Nichols method, but do not produce good control results. For this reason, more advanced tuning methods have also been developed. Examples of these, given by Liu and Daley (2001), are the automatic tuning PID and adaptive PID functions.

In practice, the PID controllers can be tuned by following the rules in Table 1. Each of the gains can be modified individually to reach the desired control result (Kiam Heong Ang et al. 2005). For example, the rise time can be decreased by increasing any of the parameters, with the greatest impact by changing the proportional gain. As can be seen from the table, the proportional and integral gains have a similar effect on the control result. The derivative term however, has the opposite effect in many cases.

Table 1. *Independent P, I and D part tuning of the PID controller. Adapted from (Kiam Heong Ang et al. 2005)*

Closed-loop response	**Rise time**	**Overshoot**	**Settling time**	**Steady-state error**	**Stability**
Increase in K_p	Decrease	Increase	Small increase	Decrease	Degrade
Increase in K_i	Small decrease	Increase	Increase	Large decrease	Degrade
Increase in K_d	Small decrease	Decrease	Decrease	Minor change	Improve

However, as mentioned by Ang et al. (2005) the parameters are not independent of each other, and changing one parameter affects the other. For this reason, tuning according to the rules given in Table 1 is not always that straightforward, and experience is needed in order to find the right control parameters.

In addition to the characteristic Ziegler-Nichols method, and the intuitive tuning based on individual PID parameters, there are many other methods as well. Alexandrov and

Palenov (2014) discuss analytic methods, frequency methods, and optimal synthesis. Examples given of the analytic tuning methods are the internal model, and lambda tuning. They are based on the algebraic or analytic dependencies between the desired control result and the system model. The frequency methods are based on the frequency characteristics of the controllable system. Lastly, the optimal synthesis methods use optimization techniques to find optimal control parameters. However, even this list is not fully extensive.

2.1.3 Feed-forward control

Feed-forward control can be added to complement the feedback control. According to Guzmán and Hägglund (2011), adding feed-forward control improves the control performance, because control action can be taken before any disturbance has affected the process output. The feed-forward path can be based on set-point following, or load disturbance rejection (Vilanova & Visioli 2012, p. 207). The feed-forward control structure is depicted in Figure 3.

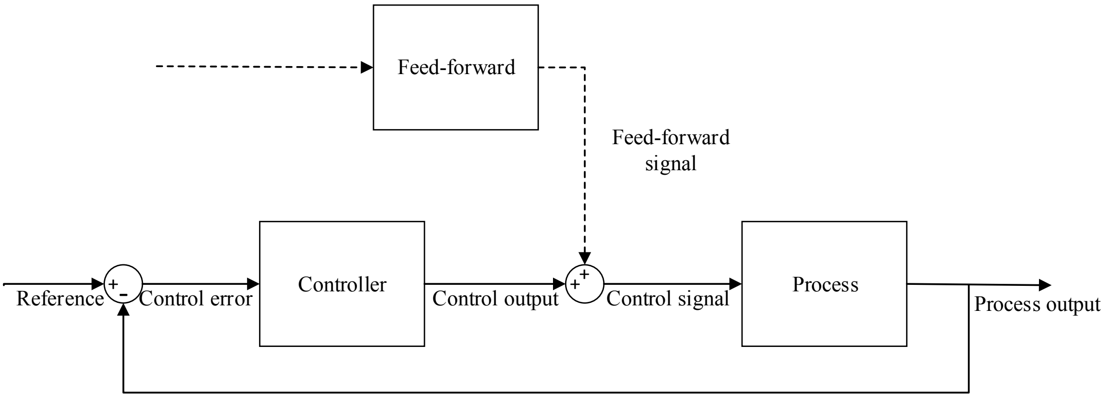

Figure 3. *Feed-forward control structure. Adapted from (Åström & Murray 2009, p. 219)*

The standard principles of feed-forward control for both set-point tracking and disturbance rejection are given by Vilanova and Visioli (2012, p. 209 & p.220-221). For set-point tracking, the reference signal is fed as an input to the feed-forward part, and the feed-forward signal is formed based on the estimation of the process model and the reference model. In turn, for disturbance rejection, the signal fed to the feed-forward compensator is the disturbance, and the aim is to design the transfer function to minimize the effect of the disturbance.

2.1.4 Adaptive PID control

In real life, the controllable processes are usually complex, and their parameters change over time. For this reason, Alexandrov and Palenov (2014) argue, that the basic PID, tuned only once, does not produce sufficient control results as time goes on. They suggest, that the PID control parameters need to be adapted based on the system dynamics in order to achieve good control results over the whole operating range.

According to Alexandrov and Palenov (2014), the adaptive PID control algorithms can be divided into direct and indirect. The direct algorithm uses the controlled variable as the basis for calculating the controller gains, whereas the indirect method utilizes the model of the controlled process and modifies the parameters according to that. The corrections to the gains can be made at intervals or continuously.

The adaptive controller based on the system operating point can be made simpler by using Gain Scheduling (GS). Alexandrov and Palenov (2014) explain, that in GS the parameters are predefined in the control design, and during operation the PID gains are looked up from the tables based on the current system state. The tables make the adaptive control simpler, and therefore GS is common in industrial applications.

Modern engine systems apply adaptive control because they are constantly evolving and becoming more complex, and thus determining of the right control parameters is increasingly difficult (Internal Wärtsilä document, 2015). Without adaptation this results in poorly tuned controls and reduces engine performance. The manual tuning tasks are also becoming more demanding, which is why many of the engine controls are tuned automatically with adaptive PID controllers. This ensures good engine performance throughout the lifetime. It also increases load response and stability.

A clear advantage gained from using the adaptive PID is that the controller gains are modified based on the operating point. This makes the control more accurate, and suitable in a wider operating range. The obvious drawback from this is that the control algorithm becomes more complex, and requires more calculation. Also, when using the tables which determine PID gains in different operating points, the tables need to be configured by an expert who knows how the control should work in different points of the operating range. Determining the desired range, how many points are needed, and the spacing between the points requires work and knowledge. However, when not using ready-made tables, an even more complex gain calculation algorithm needs to be implemented. This also requires calculation capacity, as the gains are calculated on-line.

The use of adaptive PID control is increasing as the knowledge deepens. However, as stated by Alexandrov and Palenov (2014) it is going to take some time for the actual applications to catch up on using the adaptive controller in practice. There needs to be simple and easy to understand methods to implement the adaptive PID, and the knowledge needs to be shared between developers and the operators.

3. ENGINE CONTROL REQUIREMENTS

The engine control system consists of many closed control loops, and has many controllable parameters. All of these have their own process dynamics but aim together to produce energy in the most efficient way. The main topic of this thesis are the PID controlled engine processes. Most of the PID controllers have the option to add a feed-forward action and some use the more advanced, adaptive PID control scheme.

If there is no way of measuring the performance of the many control loops, it becomes difficult to monitor and follow each control loop individually, and degraded control may not be noticed until there is a significant decrease in performance. By assessing the control performance with performance indices, it becomes easier and faster to notice and react to changing process conditions.

The engine control requirements vary depending on the operation state. In some cases, the control is required to react fast to changing set points, whereas in other occasions stable steady-state operation is desired. It should also be considered, that the real-life processes have limitations and dynamics that cannot be affected by the controller.

In this Chapter, the motivation for the control performance index is discussed. The main control requirements for the engine control system are presented briefly, with the focus on the most critical processes controlled by the PID, feed-forward or adaptive PID methods.

3.1 Motivation for the performance index development

The engine control system has numerous parameters, and many of them can be tuned during the engine lifetime. However, if there are no clear guidelines on how to tune the controllers, and what “good control” is, it is hard to achieve optimal controller performance. This can lead to quality issues, and eventually financial losses.

According to (Nordman, V. Conversation 22.2.2018), the engine control parameters are initially set based on previous engine implementations, where parameter values have been proven to work well. However, he also mentioned, that every engine is its own entity, and fine tuning of the parameter values is usually required. This is done in the laboratory. Once the engine is installed at its final location, the control parameters are once again tuned to be suitable for the specific engine, in its specific environment. Most of the control loops are tuned based on the operators’ intuition, rather than on strict rules.

According to (Brisk 2004; Yu et al. 2011; Jelali 2012), there have been many studies on control performance in the process industry, reporting far from optimal control performance. Furthermore, the controller used the most in the industry is the basic PID, and according to the studies, the poor control performance often results from poor tuning. The studies show that performance monitoring and re-tuning of the controllers is often neglected.

Having a performance index makes the tuning of the controllers easier. With a clear performance indicator, the tuning of the controller during testing and commissioning will be more straightforward, and require less time. By having a numerical value to indicate control performance, the operator will clearly see when the performance is at its best. Furthermore, the index value may provide insight to what is causing the poor performance, and thus there would be less time spent on figuring out a way to improve control performance.

The performance index provides an objective way of deciding how well the control is working. At present, the person performing the tuning task has the main responsibility to decide when the control performance is satisfactory, and the tuning is often intuitive. If the operator had the performance index as a reference, it would be easier to have more uniform control system, as the tuning result would be less dependent on who has tuned it.

The numerical performance index calculation would also be a smart investment financially. As the control performance could be made optimal from the start, the efficiency of the process would be guaranteed. Furthermore, with exact performance index, any poorly performing control loops would be more easily detected during operation and corrected with less delay. As a result, quality losses would be reduced, and product quality would stay more uniform during the lifetime of the product.

Brisk (2004), points out some additional financial benefits from optimal process controls. In addition to efficiency, process agility, and quality gains, he mentions safety and environmental impacts. With proper control performance, the probability of accidents is decreased, which in turn decreases the financial losses due to accidents. Optimally tuned controllers also reduce emissions. Brisk also states, that proper process control leads to a more sustainable manufacturing with less raw materials used, which also lowers the associated costs.

3.2 Engine control performance requirements

Engine speed and load, pressures and temperatures, as well as the combustion air/fuel ratio are all closed-loop PID controlled. Some of these controllers apply feed-forward, or adaptive PID functions. The aim for the developed performance index is that it should be able to assess the performance of these controls independent of the process being controlled. However, some of the controllers are more critical than others, and have specific requirements for their performance.

For marine engines, the Classification Societies give regulations that need to be followed. They define the technical requirements for the most important components of the vessel, including the engine, as explained in (Classification Societies - What, Why and How? 2011). These requirements provide a baseline when assessing the control performance.

The regulations only concern the most critical control loops. However, many of the control loops in the engine affect each other, and have an impact in the final power generation. This means, that if one control loop is not functioning optimally, it may result in decreasing the whole engine performance. For this reason, it is important to have all of the control loops functioning well.

One of the most important control loops is the engine speed and load control. Its performance affects greatly on the whole engine efficiency. Another important control loop is the gas pressure control. The gas pressure is a significant value, as it directly affects the combustion process when using gas as the main fuel for the engine. Furthermore, it is closely connected to the engine speed and load control.

For the engine as a whole, the control requirements vary based on the engine operation state. During the starting sequence many of the values are ramped up, and fast control response is needed. After the engine has reached the running speed, the values are kept constant. For this, stable steady-state operation is required. In turn, when the engine is stopped, the values are again ramped down, and fast and stable transient response is required. Rösgren (2016), mentions these requirements, and adds that the transient control is becoming increasingly important, and the controller's ability to respond quickly to changing operating points is closely tracked. He also suggests, that adding feed-forward control will aid in reacting fast to reference value changes.

3.2.1 Engine speed and load control

The engine speed and load control is one of the most important control tasks in an engine, as the produced power depends on it. The classification societies set requirements for controlling the engine speed. These factors are important to take into account when controlling the speed and load.

DNV GL (Det Norske Veritas Germanischer Lloyd), in their document (Part 4 Systems and components - Chapter 2 Rotating machinery, general 2018) define rules concerning the engine electric power generation. The safe value for the engine speed deviation is determined as ±5 % of the rated speed. Furthermore, the speed recovery time after a load change must equal to, or be less than five seconds, during which the speed settles within ±1 % of the reference speed.

According to (Internal Wärtsilä document, 2017), the engine speed and load can be controlled with an adaptive PID function or a regular PID function. The reference signal is calculated based on engine operation state, and current engine speed and load. The output of the controller is fuel demand. The basic structure of the speed and load controller is presented in Figure 4.

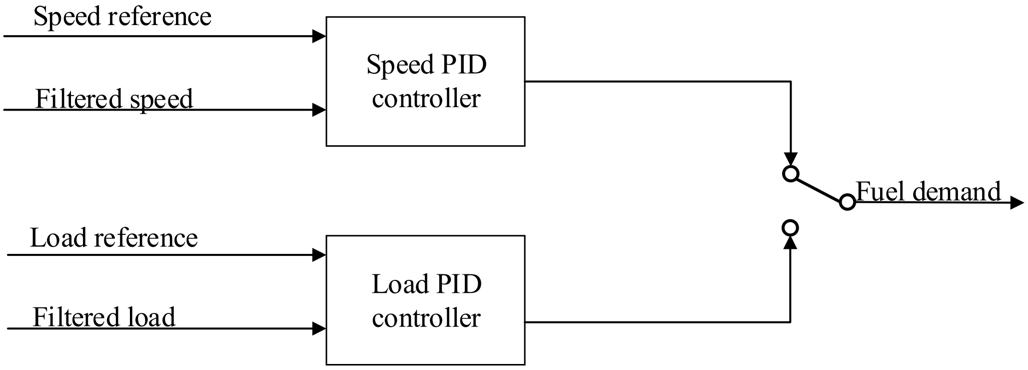

Figure 4. *Speed/load control structure. Adapted from (Internal Wärtsilä document, 2017)*

The fuel demand can be controlled with either the speed or load PID controller. According to (Internal Wärtsilä document, 2015), the controller parameters vary according to the present engine state. For adaptive PID control, the controller proportional, integral and derivative gains are calculated online.

Feed-forward control can be added to the speed and load controller to achieve better load acceptance (Internal Wärtsilä document, 2015). The function utilizes the engine load measurement and detects the changes in the engine load. This helps in minimizing load transients and unwanted deviations in engine speed. A change in engine load can be detected earlier than in speed, and therefore it is more beneficial to use that as a base for the feed-forward calculation (Internal Wärtsilä document, 2017).

The physical process naturally has some limitations for the change in speed and load. The ramp rates for both values are predetermined, and the change in operating point needs to be smooth (Internal Wärtsilä document, 2017).

3.2.2 Engine gas pressure control

For dual fuel (DF) and gas engines, the engine gas pressure is an important PID controlled variable. It affects the combustion process directly, and thus good control performance is required. Gas pressure is closely linked to the speed and load control, as it chooses its parameters according to the present engine speed or load (Internal Wärtsilä document, 2015). The basic control scheme is presented in Figure 5.

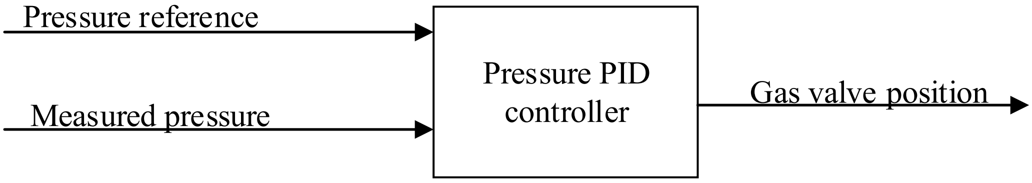

Figure 5. *Engine gas pressure control scheme. Adapted from (Internal Wärtsilä Document, 2018)*

According to (Internal Wärtsilä document, 2015), the gas pressure is controlled by changing the gas valve position. The pressure reference is calculated during operation according to the current engine state. The PID controller gains can be based either on the current engine speed or load, or the error between the measurement and reference value.

As with all the control loops, the physical limitations need to be considered. For the gas pressure control, there are limitations on how fast the gas valve position can be changed, and how quickly changing the valve position affects the gas pressure. It can be assumed that no large deviations in the gas pressure are allowed, as it affects engine combustion process and product quality.

4. PERFORMANCE INDEX THEORY

Control performance evaluation and monitoring is widely studied, and many methods have been proposed. Jämsä-Jounela et al. (2003) and Jelali (2012) have collected and evaluated many of the indices, and divided them to stochastic and deterministic methods. Jelali (2012) also introduces a group for model-based methods. Jämsä-Jounela et al. (2003) argue that indices must be chosen specific to the system operation state.

Jämsä-Jounela et al. (2003) point out, that it is often insufficient to have just one index value to assess the control performance. They suggest that different indices should be used for set-point change situations, steady-state operation and disturbance rejection. The deterministic methods are more suitable in assessing the performance during a sudden load disturbance or set-point change, and the stochastic measures are better suited when assessing the performance in steady state operation.

According to Visioli (2006), most of the performance assessment methods are based on determining a benchmark value, which the control performance is compared to. He explains that the method for finding such a benchmark value depends on the process being controlled, the controller, and the desired control result. In general, the benchmark can either be based on historical data or be calculated based on the control requirements. After the benchmark value is resolved, the measured control performance can be compared against it, and the room for improvement can be indicated by a performance index.

This Chapter first examines the common reasons for poor control performance. After this, a brief overview and history of the performance indices is presented. The factors that affect which performance index should be chosen for a specific application are briefly discussed. Lastly, the indices regarded important for engine control performance are presented in more detail.

4.1 Reasons for poor control performance

The reason why a control loop is not preforming optimally is an important aspect of control performance evaluation. A poor performing control can result from many factors, and finding out the reason is important. If the cause for poor performance is known, the improvement is more easily made.

One of the most common causes of poor control performance according to Jelali (2006), is that the parameter tuning is not done frequently enough. He explains, that the loop is commonly tuned only once during commissioning, after which the parameters are left unchanged. However, the performance of the control loop does not usually stay consistent over the years. Jelali argues that this change requires the controller to be tuned regularly in order to have consistent control performance. He also mentions that the time allocated for the tuning during the commissioning is often too short, which leads to a "good-enough" controller that never reaches its optimal performance.

For adaptive control, the changing conditions are not the main issue. As the controller parameters are constantly monitored, reaction to any change happens automatically. However, other factors may also contribute to bad controller performance. Jelali (2006) mentions, that poorly designed or malfunctioning equipment, such as sensors and actuators, may cause the control producing poor results.

Jelali (2006) continues that poor control design may be a cause for suboptimally controlled process. Lack of knowledge, or time, during the control design may lead to an inappropriate control structure. For example, the control may lack a beneficial feed-forward path.

The consequences of poor control performance may be small or severe, depending on the situation. However, even if the control performance is only slightly off from optimal, and the process is not critical, the financial or quality losses might build up over time. In critical processes the poor performing controller may even pose a safety hazard. For this reason, evaluating and monitoring the control performance should be a part of every control loop.

4.2 Methods to calculate the performance index

The interest towards control performance assessment has been growing ever since Harris published a paper about the topic in 1989. He was the first to propose using minimum variance control (MVC) as a generic benchmark for performance evaluation (Harris 1989). Since then, the topic has been greatly studied, and numerous methods have been developed to assess the performance of controllers. The minimum variance principle has been the basis of many methods, but measures based on other factors have also been studied and utilized.

As mentioned before, the control performance assessment methods can be divided into stochastic and deterministic methods. In addition to these two categories, Jelali (2012) distinguishes more advanced, model-based methods, which include the LQG (Linear Quadratic Gaussian), Generalized Minimum Variance (GMV), and Model-Predictive Control (MPC) based benchmarking as their own group. An overview of the performance assessment methods, Jelali (2012), is presented in Figure 6.

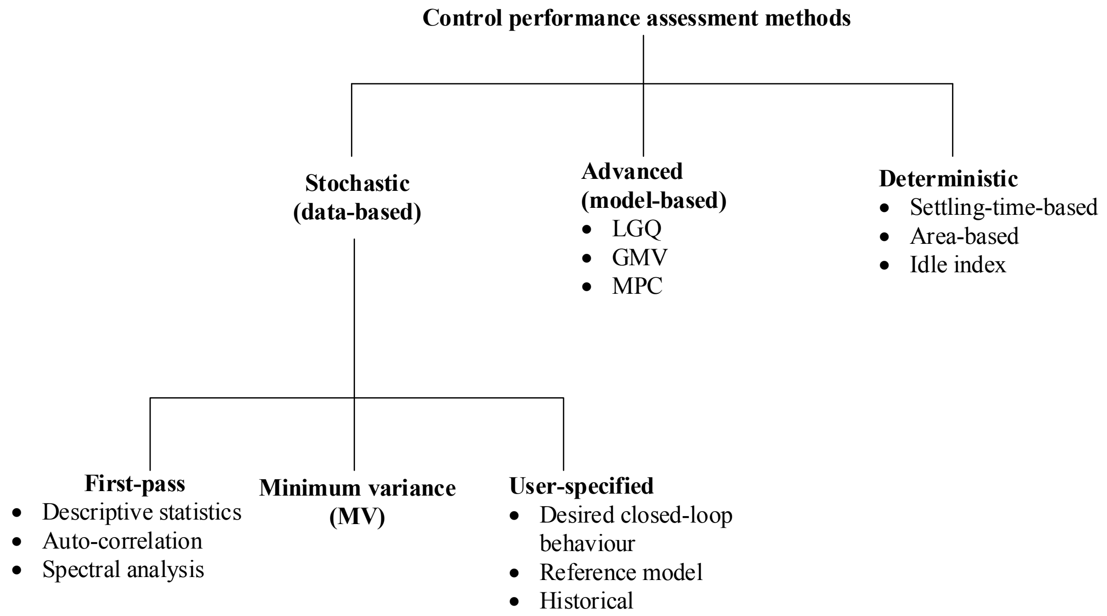

Figure 6. *Control performance evaluation methods. Adapted from (Jelali 2012, p. 12)*

The stochastic methods are data-based and the benchmark is usually based on the minimum variance control principle, Jelali (2012). Furthermore, there are many ways of using the MV (Minimum Variance) benchmark, depending on the process and controller type. Jelali mentions other stochastic measures, which are user-specified and can utilize a reference model, historical data or be based on desired closed-loop behaviour. First-pass methods include descriptive statistics, auto-correlation, and spectral analysis. According to Jämsä-Jounela et al. (2003), auto-correlation and spectral methods are especially useful in oscillation detection.

According to Jelali (2012), the deterministic methods often apply the concepts of settling time, rise time, control error, overshoot and offset values. For this reason, Jämsä-Jounela et al. (2003) suggest that deterministic methods provide more information during a set-point change or abrupt load disturbance than in steady state operation. The deterministic methods include the Idle index (Hägglund 1999), dimensionless settling time and IAE (Swanda & Seborg 1999), Absolute Performance Index (API), and the Robustness Index (RI) (Shinskey 1990).

One of the deterministic performance assessment methods is to integrate the absolute value (IAE) or the square (ISE, Integral of Squared Error) of the error signal. If the error signal is multiplied by time, the indices are ITSE and ITAE (Integral of the Time weighted Absolute Error). Dorf (1989, p. 150-152) explains, that the smaller the resulting integral value, the better the controller is working.

The indices based on error signal are easy to calculate and require only the data of the reference input and measured output. This data is usually available, so there is no need for additional measurements of the system. However, in order to determine the benchmark value, the controller should be designed by minimizing the cost function that is the

ISE, IAE, ITSE or ITAE integral. From this, the achievable minimum value for the index is obtained, and it can be compared to the index value calculated with the current error signal data.

The error signal based methods are not widely used as a performance index, at least as the sole index. However, they have been utilized to assess the control performance in some cases. Swanda and Seborg (1999) introduced the dimensionless IAE performance index and Hägglund (1995) used the IAE index to detect oscillations.

The methods described above are not the only ways to assess control performance, but the ones that appear most in the literature on this topic. They are also the ones that were considered for controller evaluation in this thesis. The field of controller performance evaluation is fairly new, and new advances are made constantly.

4.3 Choosing an index for performance assessment

The choice of the appropriate index structure depends on the dominating control task. According to Eriksson and Isaksson (1994), if the main goal is to control random, unpredictable changes in the output signal, stochastic performance assessment methods are more beneficial. However, if the main control target is to track set-point changes, or to reject periodical step output/input disturbances, the deterministic methods are suggested.

The suitable performance index for a system also depends on the control structure. If the control methods are known, their structure can be taken into account when choosing an index. Jämsä-Jounela et al. (2003) and Visioli (2006) argue that for PID control the deterministic methods are more beneficial in assessing the control performance. Both references point out that the stochastic minimum variance control may be too strict a reference, because the poor control performance may not be possible to improve by tuning the PID. According to Visioli (2006), it is more beneficial to compare the current performance to a value that is actually achievable with the used controller.

The system state during the performance assessment should also be considered when choosing the index value. If the performance during both steady-state and step-change conditions needs to be assessed, most probably multiple indices are required. According to Eriksson and Isaksson (1994), the MV based index is not the best for measuring performance during a set-point change. Jämsä-Jounela et al. (2003) state similarly that the MV index works better during steady state conditions, when the set point is constant.

When considering the indices which indices to apply, it is also important consider whether the performance is to be compared to historical values or to calculated benchmarks. A good alternative is to compare to historical data from a period when the controller was working properly. However, it raises a problem of determining when the controller performance is good enough, and during which period the controller is performing as desired. By having a calculated idealized benchmark, the actual optimality can be ensured.

Jämsä-Jounela et al. (2003) have also researched the performance assessment methods in practice, and conclude that many of them consist of multiple algorithms, which utilize the MV -based methods, autocorrelation and a range of the deterministic indices. This supports the fact that in many cases only one index value is insufficient when assessing the control performance.

Basic requirements for the performance index are given by Jelali (2012). He states, that the index should be sensitive to poor tuning, incorrect modelling, and equipment problems. Furthermore, he suggests that neither disturbances nor the set point range should affect the index, as these vary widely inside a plant. The index should also be easily implemented. It should not need any additional tests on the plant, or detailed information of the process dynamics. Lastly, the calculation should only use normal operating data of the plant. By following these principles, the implementation of the algorithm becomes easier, and the index calculation less intrusive. The focus should always be on the actual control task, and the performance assessment should bring additional value to the control operation.

It is also desirable, that the index calculation does not take much calculation power. It would be beneficial if the performance index calculation was fairly simple, and it could be easily implemented as part of the engine control applications. Therefore, for the purpose of this thesis, the chosen indices should be quite easily understandable, and they should be able to aid in the tuning of the engine controls.

4.4 Minimum variance based index

The minimum variance based performance indices are one of the most widely studied methods for controller performance assessment (Joe Qin 1998; Jämsä-Jounela et al. 2003; Jelali 2006). Harris (1989) was the first to suggest to have the minimum variance control (MVC) as a benchmark for controller performance which is theoretically the best possible. Due to his large contribution to the area, the minimum variance index has also been referred to as the Harris index (Shardt et al. 2012).

According to Jelali (2006) and (Huang & Kadali 2008) the MV benchmark calculation requires only routine operating data, and the process delay. If the delay is not known, there are methods to estimate it (Lynch & Dumont 1996). This means that the calculation of the benchmark does not need much information on the process and is relatively easy to compute.

However, when implementing the MV benchmark, it should be taken into account that the benchmark is often unrealistic and provides only a theoretical bound for control performance. As stated by Joe Qin (1998), most processes are controlled with a PID controller, and for them, reaching the MV benchmark is often impossible. For this reason, more realistic, PID focused MV benchmark values have been developed (Joe Qin 1998; Ko & Edgar 2004; Visioli 2006). These methods take controller structure into consideration when calculating the benchmark value.

Huang et al. (1997) argue, that although the MV benchmark may be far off from what is realistic, the value still provides valuable information. They propose that minimum variance based performance assessment is a good indicator on room for improvement in the controller performance by tuning or redesigning the control algorithm, or if other measures need to be taken in order to improve control performance. If the performance is far from the benchmark, it can be concluded that tuning or redesigning might be helpful. On the other hand, if the performance is close to the benchmark but the controller performance is not satisfactory, other ways such as adding a feedforward control, or shortening delay times are needed.

Many of the minimum variance benchmark methods do not specify the controller type. However, there is also a possibility to distinguish feed-forward control in the benchmark calculation. A method introduced by Vishnubhotla et al. (1997) takes the feed-forward part into account during the optimal performance calculation. The proposed feedback and feedforward minimum variance benchmark takes into account the feedforward delay in addition to the process delay.

4.4.1 Minimum variance index calculation

The MV benchmark algorithms can be defined for SISO (Single-Input, Single-Output) or MIMO (Multiple-Input, Multiple-Output) systems (Huang & Kadali 2008). In this thesis, only SISO systems are considered. A closed-loop SISO system structure is presented in Figure 7.

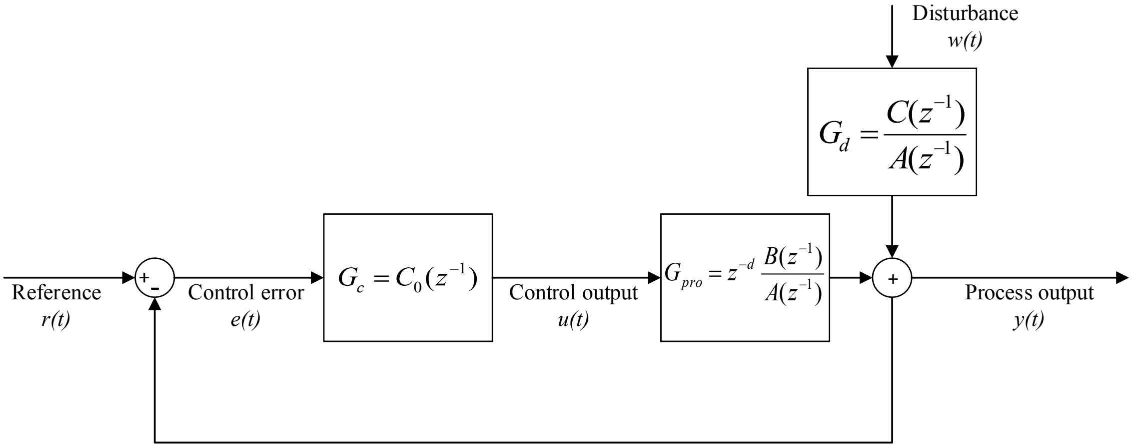

Figure 7. *Feedback control system structure. Adapted from (Ordys et al. 2007, p. 83)*

The following minimum variance analysis is based on the theory in Visioli (2006) and Ordys et al. (2007, p.83-87). The process is assumed linear, time-invariant and stationary. It is also assumed for simplicity that the reference signal is constant and zero. The SISO dynamics presented in Figure 7 is given by

$$A(z^{-1})y(t) = z^{-d}B(z^{-1})u(t) + C(z^{-1})w(t), \tag{3}$$

where d is the delay, $w(t)$ is the disturbance affecting the process output, considered as a zero mean Gaussian white noise, with a variance of σ^2, and $A(z^{-1})$, $B(z^{-1})$, and $C(z^{-1})$ are polynomials describing the process and the disturbance, and are in the form

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \dots + a_n z^{-n_A} \tag{4}$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \dots + b_n z^{-n_B} \qquad b_0 \neq 0 \tag{5}$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + c_2 z^{-2} + \dots + c_n z^{-n_C} \tag{6}$$

where $z^{-1}x(t) = x(t-1)$ is the delay operator. It is also expected, that the roots of $B(z^{-1})$ and $C(z^{-1})$ are inside the unit circle.

The goal of minimum variance control is to find the control output $u(t)$ that minimizes the output variance at time $t + d$, with the information that is available at time t. Considering this, the process output at time $t + d$ is written as

$$y(t+d) = \frac{B(z^{-1})}{A(z^{-1})}u(t) + \frac{C(z^{-1})}{A(z^{-1})}w(t+d). \tag{7}$$

The cost function to be minimized with MVC is the squared deviation of difference from reference signal (Visioli 2006) given by the following conditional expectation operator $E\{.|.\}$

$$J(t) = E\{y(t+d)^2|Y(t)\}, \tag{8}$$

where

$$Y(t) = [u(t-d-1), u(t-d-2), \dots, y(t), y(t-1), \dots]. \tag{9}$$

MVC assumes, according to Visioli (2006) that the disturbance terms $[w(t+d-1), w(t+d-2), \dots]$ do not depend on the process output $[y(t), y(t-1), \dots]$. Due to this, the disturbance signal $w(t)$ can be divided into two parts, based on if the value depends on past or future instances. Taking this, the output equation (8) is modified to

$$y(t+d) = \frac{B(z^{-1})}{A(z^{-1})}u(t) + \left[G(z^{-1}) + z^{-d}\frac{F(z^{-1})}{A(z^{-1})}\right]w(t+d), \tag{10}$$

where

$$G(z^{-1}) = 1 + g_1 z^{-1} + \cdots + g_d z^{-d}, \text{ and} \tag{11}$$

$$F(z^{-1}) = f_0 + f_1 z^{-1} + \cdots + f_{n-1} z^{-(n-1)}. \tag{12}$$

In (Visioli 2006), the previously defined polynomials further form the Diophantine equation given by

$$C(z^{-1}) = A(z^{-1})G(z^{-1}) + z^{-d}F(z^{-1}). \tag{13}$$

The equations (7), (10) and (13) are combined, and the process output at time $t+d$ is given by

$$y(t+d) = \frac{G(z^{-1})B(z^{-1})}{C(z^{-1})}u(t) + \frac{F(z^{-1})}{C(z^{-1})}y(t) + G(z^{-1})w(t+d). \tag{14}$$

Considering this, the cost function in equation (9) gets the following form

$$J(t) = E\left\{\left[\frac{G(z^{-1})B(z^{-1})}{C(z^{-1})}u(t) + \frac{F(z^{-1})}{C(z^{-1})}y(t)\right]^2\right\} + E\{[G(z^{-1})w(t+d)]^2\}. \tag{15}$$

As stated before, according to Visioli (2006), the disturbance terms $[w(t+d-1), w(t+d-2), \dots]$ and output terms $[y(t), y(t-1), \dots]$ are independent of each other. This results to the expected cross-product value of equation (15) to be zero. Due to this, the minimum variance control law can be derived from the equation, and according to Visioli (2006) it is the one that sets the first term in the equation zero. Thus, the control law can be given by

$$u(t) = -\frac{F(z^{-1})}{G(z^{-1})B(z^{-1})}y(t). \tag{16}$$

Visioli (2006) also states, that the process must be minimum phase, in particular $B(z^{-1})$ needs to be stable, for the whole closed-loop to be stable.

Now that the minimum variance control law has been established, the minimum variance based benchmark value can be calculated. The calculation procedure is the following (Visioli 2006). First, an autoregressive moving average (ARMA) model needs to be estimated from the output closed-loop data

$$y(t) = \sum_{i=1}^{n_y} a_i y(t-i) + \sum_{i=1}^{n_w} c_i w(t-i) + w(t), \tag{17}$$

where the model order is determined with (n_y, n_w), which can be found out experimentally.

Through long division the model in equation (17) can be expanded into an impulse response model, which consist of the first $d-1$ coefficients, and is the form

$$y(t) = w(t) + \sum_{i=1}^{d-1} \psi_i w(t-i). \tag{18}$$

Visioli (2006) notes that the terms of the disturbance signal up to the process delay d do not depend on the control structure, as they cannot be affected with the control signal due to the delay. Therefore, the estimated minimum variance benchmark can be calculated by

$$\sigma_{MV}^2 = (1 + \sum_{i=1}^{d-1} \psi_i^2)\sigma_w^2 , \tag{19}$$

where σ_w^2 is the variance of the estimated noise.

The established benchmark value can be compared to the estimate of the current output variance that can be calculated by

$$\sigma_y^2 = \frac{1}{N-1} \sum_{i=1}^{N} (y(i) - \bar{y})^2, \tag{20}$$

where the mean of the process output is $\bar{y}$. The final minimum variance index is obtained by comparing σ_y^2 to the benchmark σ_{MV}^2

$$I = \frac{\sigma_y^2}{\sigma_{MV}^2}. \tag{21}$$

This index value can range from $[1, +\infty)$. A value close to one means that the controller performance is close to optimal, and a value much larger than one suggests that the control performance is inferior to MV and can possibly be improved (Visioli 2006).

An unbounded index is easier to interpret. Thus, more commonly a performance index η normalized to [0, 1] is applied, Visioli (2006):

$$\eta = 1 - \frac{\sigma_{MV}^2}{\sigma_y^2} = \frac{\sigma_y^2 - \sigma_{MV}^2}{\sigma_y^2}. \tag{22}$$

Value close to one means poor control performance, and a value close to zero good performance.

The benchmark value can also be reversed, with one meaning good control performance, and zero meaning poor performance. This kind of index value is used by Ordys et al. (2007, p.83-87), where the normalized index value is calculated by dividing the optimal benchmark σ_{MV}^2 with the actual variance of the output σ_y^2. Because there are different modifications of the index value, it should be stated clearly during implementation, how the value is to be interpreted.

4.4.2 Direct least-squares estimation

There are also methods that can be used to provide a simplified estimate of the index value. For example, direct least-squares algorithm has been introduced by Desborough and Harris (1992). The linear regression approach makes the index calculation simpler, due to it allowing the normalized index to be calculated from routine operating data, without having to calculate the Diophantine equation, or preform the long division.

The direct least-squares estimation method is also discussed by Ordys et al. (2007, p.83-87). According to them, from Equation (14), using $u(t) = -C_0(z^{-1})y(t)$, the process output can be modified to

$$y(t) = z^{-d}\left(\frac{F(z^{-1}) - G(z^{-1})B(z^{-1})C_0(z^{-1})}{C(z^{-1})}\right)y(t) + G(z^{-1})w(t+d). \tag{23}$$

Because the closed-loop is expected to be stable the first part of the Equation (23) can be approximated by a finite length autoregressive model (AR), and the output transforms to

$$y(t) = \sum_{i=1}^{m} \alpha_i y(t-d-i) + G(z^{-1})w(t), \tag{24}$$

where m is the length of the autoregressive model.

For estimating the α_i parameters Ordys et al. (2007, p.83-87) use the following matrix equation

$$\boldsymbol{y} = \boldsymbol{X\alpha} + \boldsymbol{G}w, \tag{25}$$

in which

$$\boldsymbol{X} = \begin{bmatrix} y_n & y_{n-d-1} & \cdots & y_{n-d-m+1} \\ y_{n-d-1} & y_{n-d-2} & \cdots & y_{n-d-m} \\ \vdots & \vdots & \ddots & \vdots \\ y_m & y_{m-1} & \cdots & y_1 \end{bmatrix} \boldsymbol{y} = \begin{bmatrix} y_n \\ y_{n-1} \\ \vdots \\ y_{d+m} \end{bmatrix} \boldsymbol{\alpha} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_m \end{bmatrix}, \tag{26}$$

where n is the sample length.

Using linear regression they calculate the autoregressive parameters by

$$\hat{\alpha} = (\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{y}. \tag{27}$$

An estimate for the minimum variance value can now be calculated as the residual variance

$$\hat{\sigma}_{MV}^2 = \left(\sum_{i=1}^{d-1}\psi_i^2\right)\sigma_w^2 = \frac{1}{n-d-2m+1}(\mathbf{y} - \mathbf{X}\boldsymbol{\alpha})^T(\mathbf{y} - \mathbf{X}\boldsymbol{\alpha}), \tag{28}$$

and the actual output variance is

$$\hat{\sigma}_y^2 = \frac{1}{n-d-m+1}\mathbf{y}^T\mathbf{y}. \tag{29}$$

Equations (28) and (29) are combined, and the normalized MV performance index becomes

$$\hat{\eta} = 1 - \frac{\hat{\sigma}_{MV}^2}{\hat{\sigma}_y^2} = 1 - \frac{n-d-m+1}{n-d-2m+1}\frac{(\mathbf{y}-\mathbf{X\alpha})^{\mathbf{T}}(\mathbf{y}-\mathbf{X\alpha})}{\mathbf{y}^T\mathbf{y}+(n-d-m+1)\bar{y}^2}. \tag{30}$$

Ordys et al. (2007, p.83-87) note, that this method calculates the index during a constant set point. If the index is calculated during a set point change, the output $y(t)$ should be replaced with the error signal $e(t) = r(t) - y(t)$.

4.4.3 Recursive least squares estimation

For online estimation and tuning, according to Desborough and Harris (1992) and Jelali (2012), the recursive least squares method is especially useful. The cost function to be minimized with the recursive least squares is given as

$$V = (\mathbf{y} - \mathbf{X\alpha})^T\mathbf{\Lambda}(\mathbf{y} - \mathbf{X\alpha}), \tag{31}$$

where $\mathbf{\Lambda}$ is a diagonal matrix with $(\lambda, \lambda^2, \dots, \lambda^N)$ as the diagonal elements. The diagonal element λ is the forgetting factor, which puts more emphasis on recent data.

By utilizing the forgetting factor, an estimate of the minimum variance benchmark at a time k is calculated by Jelali (2012) with

$$\sigma_{MV}^2(k) = \lambda\sigma_{MV}^2(k-1) + w^2(k). \tag{32}$$

The value that the benchmark is compared to is the exponentially weighted moving mean square error, which can be calculated by

$$\sigma_y^2(k) = \lambda\sigma_y^2(k-1) + y^2(k). \tag{33}$$

Using (32) and (33) an estimate of the MV performance index at a time k can be given by

$$\hat{\eta}(k) = \frac{\sigma_{MV}^2(k)}{\sigma_y^2(k)}. \tag{34}$$

This index value is limited between [0, 1]. A value close to one indicates a good performing control and close to zero indicates a poor performing control (Jelali 2012).

4.4.4 Filtering and correlation analysis

Filtering and correlation analysis (FCOR) is a third way to estimate the minimum variance benchmark value. According to Jelali (2012) the method is further simplified, as it does not need the calculation of the impulse response coefficients. He explains, that is based on filtering or pre-whitening the system output data, and then calculating the correlation between the delay-free output and estimated disturbances from the filter.

The FCOR benchmark calculation procedure is explained by Olaleye et al. (2004). First, they present the impulse response of the model as

$$y(k) = \left(\textstyle\sum_{i=0}^{\infty} \psi_i \, z^{-i}\right) w(k) \tag{35}$$

$$= \left(\psi_0 + \psi_1 z^{-1} + \psi_2 z^{-2} + \cdots + \psi_{d-1} z^{-(d-1)}\right) w(k) \tag{36}$$

$$+(\psi_d z^{-d} + \psi_{d+1} z^{-(d+1)} + \cdots) w(k) \tag{37}$$

where the function is divided into the feedback-invariant and feedback-varying parts respectively. The equation is then multiplied with $w(k), w(k-1), \ldots, w(k-d+1)$, and the expectation of both sides of the equation is taken, which results to

$$r_{yw}(0) = E\{y(k)w(k)\} = \psi_0 \sigma_w^2,$$

$$r_{yw}(1) = E\{y(k)w(k-1)\} = \psi_1 \sigma_w^2,$$

$$r_{yw}(2) = E\{y(k)w(k-2)\} = \psi_2 \sigma_w^2,$$

$$\vdots$$

$$r_{yw}(d-1) = E\{y(k)w(k-d+1)\} = \psi_{d-1} \sigma_w^2 \tag{38}$$

From this, the minimum variance of the feedback-invariant part is

$$\sigma_{MV}^2 = \textstyle\sum_{i=0}^{d-1} \psi_i^2 \, \sigma_w^2 = \sum_{i=0}^{d-1} \left(\frac{r_{yw}(i)}{\sigma_w^2}\right)^2 \sigma_w^2 = \sum_{i=0}^{d-1} \frac{r_{yw}^2(i)}{\sigma_w^2}. \tag{39}$$

Substituting the benchmark value in (39) to equation (34) gives the minimum variance performance index as

$$\eta_{MV,cor} = \textstyle\sum_{i=0}^{d-1} \frac{r_{yw}^2(i)}{(\sigma_w^2 \sigma_y^2)} = \sum_{i=0}^{d-1} \rho_{yw}^2(i) = \boldsymbol{Z}^T \boldsymbol{Z}, \tag{40}$$

where $\boldsymbol{Z}$ is the cross-correlation coefficient vector between the output $y(k)$ and the disturbance $w(k)$ for lags from 0 to $d-1$. It can be given by

$$\boldsymbol{Z} \equiv [\rho_{yw}(0), \rho_{yw}(1), \rho_{yw}(2), \ldots, \rho_{yw}(d-1)]^T \tag{41}$$

The sampled version of the performance index can be given by

$$\hat{\eta}_{MV,cor} = \sum_{i=0}^{d-1} \hat{\rho}_{yw}^{2}(i) = \hat{\boldsymbol{Z}}^{T}\hat{\boldsymbol{Z}} \,,$$

where the cross-correlation coefficient is

$$\hat{\rho}_{yw}^{2}(l) = \frac{\sum_{k=1}^{M} y(k)w(k-l)}{\sum_{k=1}^{M} y^{2}(k) \sum_{k=1}^{M} w^{2}(k)} \tag{42}$$

According to Olaleye et al. (2004), the disturbance term $w(k)$ can be determined from the pre-whitening of the process output by time-series analysis.

According to (Jelali 2012) the time-series analysis can be based on, for example, the AR model in Equation (24) or the ARMA model given in Equation (17). He gives an example where the ARMA model is inverted, and an estimate for the disturbance is obtained by

$$\boldsymbol{w} = \hat{C}^{-1}(z^{-1})\hat{A}(z^{-1})\boldsymbol{y}, \tag{43}$$

where $\boldsymbol{y}$ is a vector consisting of the output data. This estimated disturbance value can be further utilized in the correlation analysis procedure.

4.5 Index for set-point change

A common way to evaluate the closed-loop performance is presented in Dorf (1989, p.133-139). It is based on feeding a step input to the system, and evaluating how quickly and accurately the output reaches the desired step value. Alternatively, the input may be a ramp or a parabolic function of time. The use of such test inputs is common, because it is easy to compare control structures and methods in tests with the same type of input signals. An example of a control system step response is presented in Figure 8.

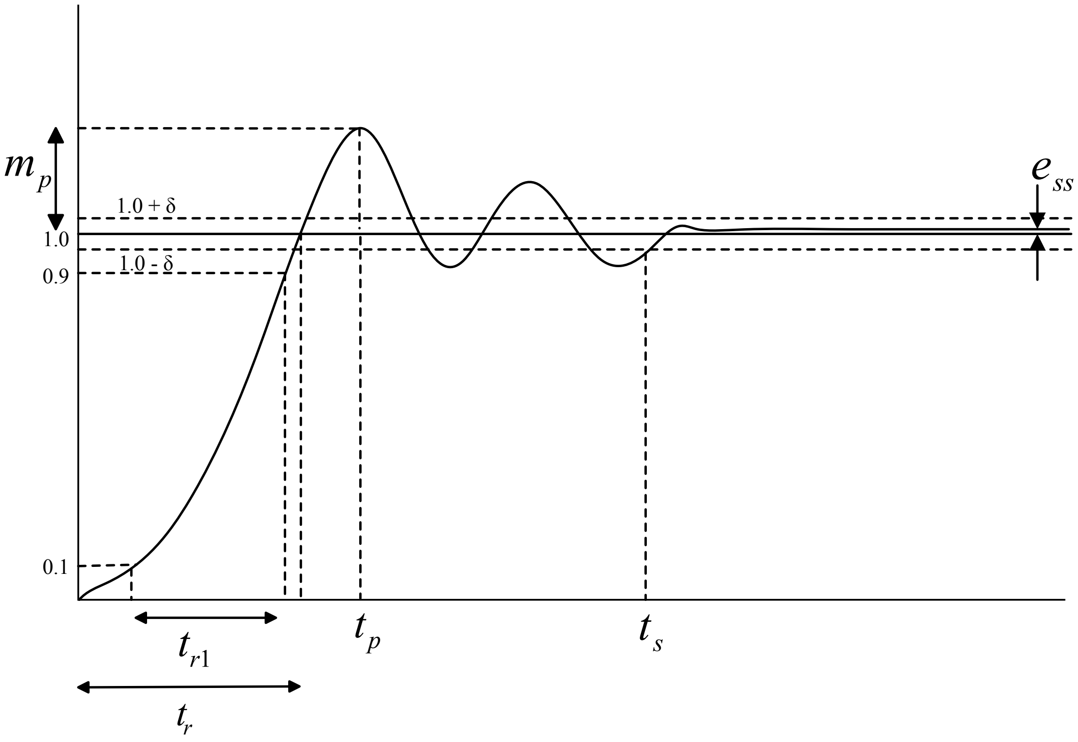

Figure 8. *Step-response model. Adapted from (Dorf 1989, p. 138)*

In Figure 8 the settling time of the step-response is t_s. It represents the time that it takes for the output to reach the desired value within. δ is a given portion of the requested amplitude change. The overshoot of the step-response m_p, and the time of the peak response is t_p. Overdamped systems do not have overshoot or time of peak response. Figure 8 indicates two rise times, t_{r1} and t_r, the first is used for overdamped systems, and the second for underdamped systems with overshoot.

The remaining steady-state error is marked as e_{ss} in Figure 8. According to Dorf (1989, p.133-139), if the system has at least one integrator, the steady-state error is zero when feeding a step input to the system. Therefore, if a PI or PID controller is used, the system response will reach the desired step magnitude, and e_{ss} will be zero.

Requirements can be based on several step response parameters. If the system response is required to be fast, a maximum value for the rise time can be set. If a more stable response is desired, maximum overshoot and settling time are specified. However, as stated in Dorf (1989, p.133-139), the fastest and most stable response cannot be obtained simultaneously, and a compromise between the two must always be made.

Swanda and Seborg (1999) utilize the step response parameters in performance assessment. They calculate the dimensionless settling time by utilizing the apparent time delay, and the settling time. They calculate the dimensionless settling time by

$$T_s = \frac{t_s}{\theta_a}, \tag{44}$$

where t_s is the time it takes for the process output to reach the reference value within $\delta = 0.1$, and θ_a represents the net effect of the time delays, right half plane zeros, and process order.

Swanda and Seborg (1999) pair the dimensionless settling time with the dimensionless IAE index. This allows the inspection of the entire response, rather than a single point. The dimensionless index value is calculated by

$$IAE_d = \frac{IAE}{|r_0|\theta_a}, \tag{45}$$

where r_0 is the step change size.

According to these dimensionless values, and the overshoot of the measurement signal, three performance classes are defined by Swanda and Seborg (1999) for different PI-controller characteristics. These are the high performance, excessively sluggish, and poorly tuned controllers. The requirements for each class are defined in Table 2.

Table 2. *Performance classes for a PI controller. Adapted from (Swanda & Seborg 1999)*

Performance class	T_s	IAE_d	Overshoot
High performance	≤ 4.6	≤ 2.8	Not specified
Excessively sluggish	> 13.3	> 6.3	$\leq 10\ \%$
Poorly tuned	> 13.3	> 6.3	$> 10\ \%$

It is worth noting, that the values in Table 2 are defined for a PI controller, because Swanda and Seborg (1999) demonstrate the performance assessment measures only for PIs. As PIs are more common than full PIDs these benchmark values are quite useful. However, Swanda and Seborg (1999) state that the method is also suitable for a PID controller, but do not provide evidence for this. Thus, special attention should be paid when using a full PID controller.

Åström et al. (1992) define a dimensionless rise time. However, this method is especially designed for PID controllers tuned with the Ziegler-Nichols formula. The method is based on using the apparent dead time of the open-loop system to define a good rise time. Åström et al. (1992) specify that rise time equal to the apparent dead time indicates good control performance for stable processes with no integral action. For integrating processes, the rise time should equal to half of the apparent dead time.

4.6 The Idle Index

According to Jämsä-Jounela et al. (2003), the idle index is a dimensionless, deterministic performance assessment measure. It detects too conservative tuning during sudden load disturbances. Hägglund (1999) states that the index is based on the relationship between the measured variable and the control signal. The underlying idea can be seen from Figure 9.

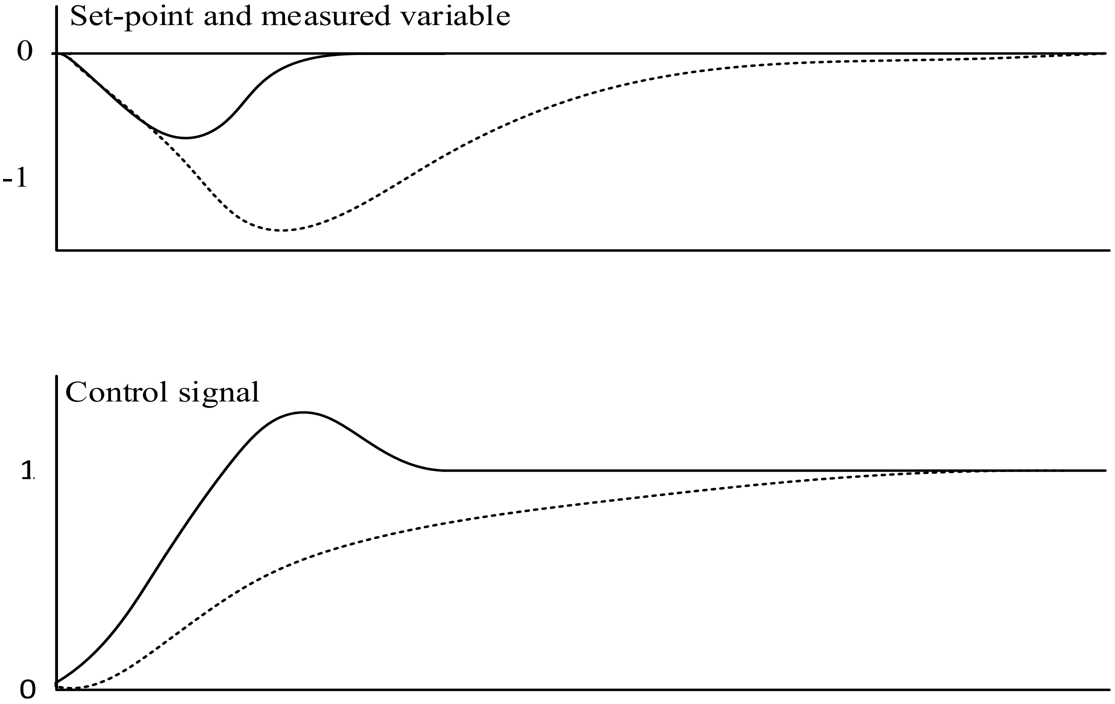

Figure 9. *Principle of the idle index. Adapted from (Hägglund 1999)*

Figure 9 shows two control results of a stepwise load disturbance in the process input. The solid line depicts fast response and rapid restoration of the desired value. The dashed line, however, depicts slower response and a longer restoration time. According to Hägglund (1999), the idle index is used to detect this slow change by inspecting the correlation between the measured variable and control signal increments. During the slow response, the correlation is positive, as both of the signals are heading to the same direction.

The idle index calculation procedure is established by Hägglund (1999). In order to calculate the index value, the periods during which the correlation of the signal increments is positive or negative are first calculated. At every sampling instant, the positive and negative correlations can be calculated as follows

$$t_{pos} = \begin{cases} t_{pos} + h & if\ \Delta u \Delta y > 0 \\ t_{pos} & if\ \Delta u \Delta y \leq 0 \end{cases} \tag{46}$$

$$t_{neg} = \begin{cases} t_{neg} + h & if\ \Delta u \Delta y < 0 \\ t_{neg} & if\ \Delta u \Delta y \geq 0 \end{cases} \tag{47}$$

where h is the sampling period.

Based on these values, the idle index is calculated by Hägglund (1999) with

$$I_i = \frac{t_{pos} - t_{neg}}{t_{pos} + t_{neg}}. \tag{48}$$

The idle index presented is bounded between [-1, 1]. If the index value is positive, and close to 1, the control is interpreted sluggish.

When implementing the idle index on-line, Hägglund (1999) recommends to calculate the index value recursively. The following procedure, updated at every sampling instant, is suggested,

if $\Delta u \Delta y > 0$ then $s = 1$

else if $\Delta u \Delta y < 0$ then $s = -1$

else $s = 0,$ (49)

if $s \neq 0$ then $I_i = \gamma I_i + (1 - \gamma) s,$

where the parameter γ determines the time horizon.

In off-line calculations Hägglund (1999) suggests that the signals are observed over a supervision time $T_{sup} = t_{pos} + t_{neg}$. The time horizons for off-line and on-line index calculation are related by

$$\gamma = 1 - \frac{h}{T_{sup}}. \tag{50}$$

According to Hägglund (1999), the time horizon T_{sup} should be long enough, that at least one load disturbance occurs during it. Furthermore, if load-detection is used, T_{sup} should cover the whole load transient. The value of γ can be calculated using the above equation, based on T_{sup}. However, Hägglund notes that usually there is less information available when calculating off-line.

It is advised by Hägglund (1999) that the idle index calculation should not be performed during steady-state conditions. It is suggested, that the control is done only when the absolute value of the control error goes above a certain predetermined limit. According to Hägglund, this limit can be based on an estimate of the noise level, or given a fixed percentage value.

According to Hägglund (1999), as the idle index deals with signal increments, the noise affects the calculations quite significantly and needs to be taken into account. Thus, filtering the signals is recommended before the index calculation. Hägglund states, that various filtering techniques can be used to reduce the noise.

The importance of filtering the idle index algorithm input signals is discussed by Kuehl and Horch (2005). Three filtering techniques are proposed: reinitialized lowpass filter, linear regression filter, and wavelet denoising. No guidelines to choose a filtering method are provided, other than claiming it to depend on the application.

Other data pre-processing measures are also suggested by Kuehl and Horch (2005). They advise, that after filtering the data, the steady-state portion should be removed, and the signal should be quantized. All of these methods are claimed to improve the performance assessment of the idle index.

The way to interpret the index value is presented in Table 3. A negative index value can be a result of an oscillatory or well-tuned control. This is why Hägglund (1999) states that no clear conclusion of the control performance can be given based on the negative idle index alone. He suggests to use an oscillation detection method together with the idle index. This way the idle index can be disregarded or the calculation can be stopped when an oscillation is present.

Table 3. *Idle index interpretation Hägglund (1999).*

Idle index	Interpretation
Negative value	Well-tuned control, oscillatory control
Small values $(-0.4 < I_i < 0.4)$	Well-tuned control
Large positive value	Sluggish control

According to Hägglund (1999), small values of the idle index, both negative and positive, indicate that the controller is well-tuned. Sluggish control is detected when the idle index is close to one. Hägglund (1999) emphasizes, that indicating sluggish control is the main purpose of the idle index.

Hägglund (1999) also points out the limitations of the index. First is that it might detect the control to be sluggish if load disturbances are varying slowly. In other words, the index gives reliable results only when load changes are abrupt, or step like. Therefore, it is suggested, that the index should only be calculated when there are sudden load changes, which can be detected by using load-detection methods.

Additionally, as reported by Hägglund (1999), the idle index does not detect sluggish control if there is an overshoot in the control signal. This is because the correlation between the control signal and measured variable is not negative during the overshoot, which results in smaller idle index value. It can be concluded that the idle index only works in detecting conservative control when there is no overshoot in the control signal.

Other considerations of idle index include that some control loops might be tuned to be more sluggish on purpose (Kuehl and Horch (2005). This means that a larger index value is to be expected. The period over which the index is evaluated should be long enough that the index values has time to settle, but short enough that the calculation values do not increase too much (Kuehl and Horch (2005). A solution for this is to reset the values in certain intervals.

4.7 Oscillation detection

The tendency to oscillate is an important performance measure of the controller. Oscillation can be caused by friction in the control valve, bad controller tuning, or oscillating disturbances (Hägglund (1995). Furthermore, it can lead to energy, and material losses, and may affect negatively in the quality of the product being manufactured.

Hägglund (1995) presents a non-intrusive and automatic method to detect oscillation. The calculation does not require any parameters or other information specified by the user. The oscillation detection method is based on the integral of the absolute error (IAE). The IAE value for oscillation detection is defined as

$$IAE = \int_{t_{i-1}}^{t_i} |e(t)| \, dt \tag{51}$$

where e is the error signal, and t_{i-1} and t_i represent two consecutive instances of zero crossings of the control error. Hägglund notes, that the method assumes that the controller is integrative, which means that the average control error is zero, i.e. if the integral gain of the PID controller is nonzero.

Hägglund (1995) utilizes the IAE value to detect load disturbances. When the calculated IAE is small, which means that the control error is small, the control is functioning well. When the IAE increases, the time between the zero crossings increases, and a load disturbance is detected when the value of IAE exceeds a certain limit. This limit is defined as

$$IAE_{lim} = \frac{2a}{\omega_u}. \tag{52}$$

If the calculated IAE value exceeds this limit, it can be concluded that a load disturbance has occurred. The threshold value depends on the acceptable oscillation amplitude a, and the ultimate frequency of the process ω_u. However, if the ultimate frequency is not available, it can be replaced with $\omega_i = 2\pi/T_i$, and the limit becomes

$$IAE_{lim} = \frac{aT_i}{\pi} \tag{53}$$

where T_i is the integral time constant. Hägglund notes, that if the controller is not properly tuned, using the integral time constant may produce inaccurate results. A suitable value for the acceptable oscillation term is given to be $a = 1\%$.

Hägglund (1995) continues that the presence of oscillation can be determined by calculating the times that load disturbance occurs. If the amount of load disturbances during a predetermined time, $T_{sup} = 50T$, where T can be the ultimate period of the process T_u, or the integral time constant T_i, exceeds a threshold limit, given by Hägglund as $n_{lim} = 10$, oscillation is present.

Hägglund (1995) suggests, that rather than using the sum of the load disturbances directly, it is more effective to calculate the sum of the load disturbances using exponential weightings. The following algorithm is given to sum the load disturbances

$$x = \gamma x + load, \tag{54}$$

where the $load$ term is either a zero or one depending on whether a load disturbance has been detected. This procedure is updated at every sampling instant. Now, when the value of x exceeds n_{lim} oscillation is detected.

For the calculation of the weighting parameter γ, Equation (50) can be used. The supervision time can be calculated according to (Hägglund 1995), by utilizing the n_{lim} value, and the integral time constant T_i as follows

$$T_{sup} = \frac{n_{lim}T_i}{2}. \tag{55}$$

The supervision time is suggested to be multiplied before the γ calculation, to better detect oscillations with a longer time period. If the oscillation frequency is lower, the IAE value is calculated for longer, which decreases the sum x, as the $load$ is zero during this time, this makes it harder for the sum to exceed the limit. By increasing the supervision time, the γ value, calculated using Equation (50), increases. This allows for the sum in Equation (54) to update with larger increments, and thus the sum of load disturbances will exceed the limit value faster, and oscillation will be detected.

5. INDEX IMPLEMENTATION

The algorithms presented in the previous Chapter are implemented as the performance index calculation in MATLAB Simulink. As one index is insufficient to assess control system performance, multiple indices are implemented and tested. However, for the ease of use of the indices, the number of indices is kept small. The indices are initially tested on a simple second order transfer function being controlled with a PID controller.

In this Chapter, the indices chosen to be implemented are first discussed. Then the closed-loop system used for testing the functionality is described. The implementation of the indices is discussed next, and finally the indices are roughly validated.

5.1 Chosen indices for engine control performance evaluation

The index should indicate the control performance in an easily interpreted way. Furthermore, the algorithm should be fairly simple, and be computationally efficient. It is desirable that the index is easily implemented independent on the type of the control loop. The number of application-specific parameters should be minimized, because the index should work independently and automatically with little need for modifications.

The performance assessment algorithm should also be able assess the performance both in set-point change situations and during steady-state conditions. This requires more than one index. The indices chosen to be implemented were the dimensionless IAE and settling time, idle index and oscillation detection. These assess the various aspects of control performance. To support these, the rise time, settling time, estimation of the delay, and overshoot are calculated.

The minimum variance control based index was also considered. The reasons were its popularity, and suitability for steady-state performance assessment. However, the index algorithm was more complicated than the other chosen indices, and the implementation would have taken a lot of time. It was also pointed out in the theory that the calculated benchmark value may not be achievable with a PID controller, thus making the index hard to interpret and less valuable. Due to these reasons, the MV based index was not chosen to be implemented in the scope of this thesis.

The dimensionless values focus on assessing the performance during set-point changes. They indicate if the controller reacts quickly enough to the changing reference value. The idle index detects how well the controller reacts to sudden disturbances during steady-state operation. It can also be used as an aid to assess the control performance during set-point changes. The oscillation detection method detects oscillations in the measurement signal due to poor controller tuning, or disturbances during steady-state operation. The overshoot value indicates the magnitude of the deviation in stepwise set-point changes, and stepwise load distributions during steady state conditions.

All the selected methods are fairly simple to understand and compute. They also give a good indication of the performance in different system states. In the future, the minimum variance based index value can be developed, if these methods do not prove to give sufficient performance assessment results.

5.2 Closed-loop system for initial testing

When implementing the index values it is important to test and verify the functionality with a simple process model and a basic PID function, before assessing the performance of the actual engine controls. This way the functionality can be verified, and possible modifications can be made more easily. In principle, the process model should not affect the functionality of the performance assessment. However, even if the calculations work well using these simple models, it does not guarantee that they work in an actual engine.

For the initial testing of the performance assessment measures, a simple PID function and process model were implemented. A basic PID with a derivative filter was chosen. The process was depicted with a simple and stable second order model given by

$$G_{pro} = \frac{e^{-s}}{s^2+2s+1}. \tag{56}$$

This model structure was used by Åström et al. (1992) to test index functionalities, and thus it was determined suitable for testing the functionality of the chosen indices.

The resulting closed loop system connected to the performance assessment is presented in Figure 10. Different reference values and controller parameters can be used in simulation to verify the index functionalities in varying conditions. The index calculations require the control signal, the proportional and integral gains, the reference value, and the measurement signal, which all can be easily obtained.

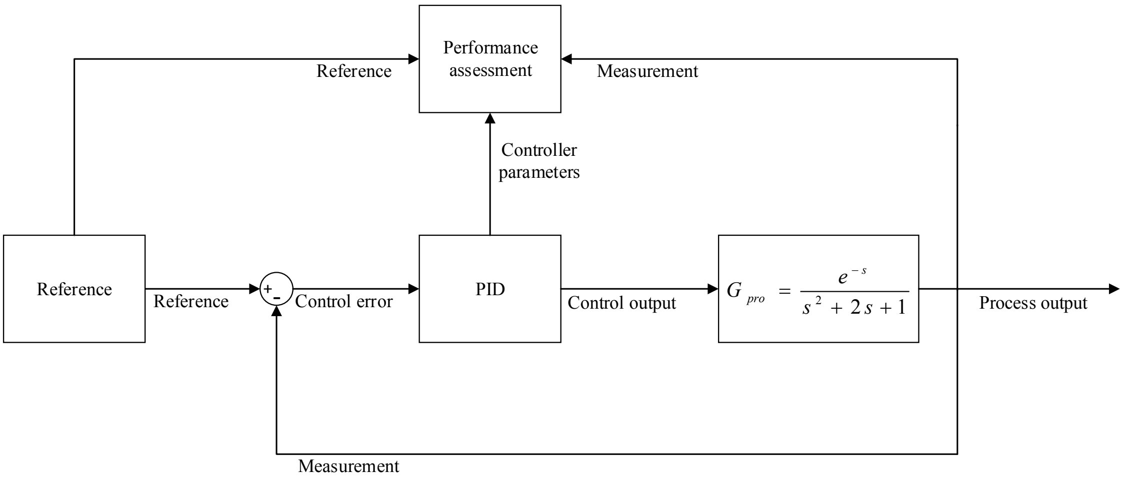

Figure 10. *Closed-loop system for performance assessment implementation verification.*

The closed-loop control system is implemented in the Wärtsilä Simulink Development Environment (WSDE). The environment allows for testing the index functionality using the same functions and blocks as in the final engine control applications. A discrete-time PID controller with a derivative part filter, which is also utilized in some of the engine control applications, is used to test the index implementation. The discrete PID function output is used to control the continuous-time process. The PID controller sample time is 100 ms. The continuous time process is integrated using the Euler method, with a fixed step size of 100 ms.

The engine controls only use integers, and thus the index calculation is required to be performed in integers. This requires some scaling of the values in order to preserve accuracy. The performance assessment algorithms are connected to the PID controller in the discrete side, and thus their sampling time is 100 ms.

5.3 Implementation of the set-point change index

For set-point change performance assessment, the main indices are the dimensionless settling time and the dimensionless IAE index. The values for settling time, rise time and overshoot are also calculated. The indices were defined in Section 4.5. All of them can be calculated using the reference and measurement signals.

The rise time, settling time and estimated delay are calculated in a Simulink Stateflow chart. The calculation of the values starts when a change in the set-point is detected. The calculation is updated at every sampling time, by adding the sample time to the previous calculated time value. The delay is started to be calculated first, and stopped when the measurement value changes. Then, the settling time and rise times are started to accumulate. The rise time accumulation is stopped once 95 % of the step magnitude is reached. The settling time calculation is stopped when the error is permanently within ±1 % of the reference. If the measurement deviates outside this range once it has reached it the first time, the settling time calculation continues. This way, if there is a passing oscillation in the signals, that time is also included in the settling time. The method does not consider the fact that the measurement signal might have noise that exceeds this range.

If the measurement deviates outside the range of ±1 % of the set-point after 1000 or more time steps, the settling time calculation is reset. This way, the settling time value can also be used to indicate the time it takes to recover from disturbances that happen during steady-state conditions, after reaching the desired reference value. However, in this case the settling time is not the correct term to be used, as it is reserved for indicating the step-response characteristics.

The dimensionless settling time is calculated using Equation (44), and the dimensionless IAE value with Equation (45). Both dimensionless index values are scaled by multiplying them by ten. Some accuracy is inevitably lost due to integer number use. The indices are reset every time the set-point changes.

The overshoot calculation is done by first detecting if the reference value is increasing or decreasing. If the reference increases, the overshoot is calculated when the error (reference - measurement) is negative. In turn, if the reference decreases, overshoot is present when the error is positive. The resulting overshoot is the biggest absolute error. The overshoot value is multiplied by a hundred, and given as a percent of the reference value, to reach better accuracy when using integers. For even more accuracy, the scaling factor can be increased.

To make the performance assessment easier, a combined step response index was created based on Table 2. Each of the classes were given a numerical value that indicates the control performance. In case of a high-performing controller, the combined index value is set to -2, and for sluggish control result the value is set to 1, and for poor control to 2. This was implemented in Simulink with an If block.

In addition to the three classes given in Table 2, a control performance class was created for situations when either the dimensionless settling time or the IAE value is within the high-performance limit. The combined index value is set to -1 if one of the dimensionless values satisfies the high performance criteria. However, if the other value exceeds the poor/sluggish control limit, the requirements for this class are not met.

These four classes combine the dimensionless values and the overshoot value, which makes the interpretation of the control performance much simpler. The positive index values indicate that the control performance should be improved, and the negative values indicate that at least one of the dimensionless values is within the high performance range.

5.4 Implementation of the idle index

The idle index can be used to detect sluggish control during sudden load disturbances, and during set-point changes. It was implemented based on Section 4.6. The calculation consists of the correlation calculation and the actual index calculation algorithms. In the correlation calculation, the control output and measurement values are used to form the correlation parameter $\Delta u \Delta y$. This value is then used to calculate the idle index value.

The idle index is implemented using the recursive algorithm. At every sampling instant, the value of s is updated per the sequence given in Equation (50). The value is then forwarded to the actual index calculation. The index value calculation is not done if $s = 0$, and the index value is frozen to its current value. If the correlation parameter s is not zero, the idle index value is calculated using Equation (49), and the time constant γ is calculated with Equation (50). The supervision time is given a default value of 2000 ms, but it can be modified if needed.

For the calculation to function in an engine control system, integer values must be used. Thus, the default range for the index value, $[-1, 1]$ does not provide an accurate result as values in between the integer values are also required. For this reason, the index value is scaled by multiplying it by 1000. Thus, the range for the idle index is $[-1000, 1000]$.

The idle index value is not calculated if the error is within two percent of the reference value. This ensures, that unnecessary calculation is not made during steady state conditions, or during small deviations from the set-point. The calculation is reset if there is a change in the reference value, or the control error is zero. This way each new step change or disturbance situation can be evaluated starting from zero.

One of the limitations of the calculation is that it detects false good control if an oscillation is present. This is coped with by implementing an oscillation detection method. If oscillation is present, the idle index calculation is reset and kept at zero until the oscillation is no longer present.

For this implementation, a filter for the measurement and control signals was not included. This is because in the engine, the values are already filtered before entering the index calculation. For further development of the index value, a filter of the input signals could be implemented. As mentioned in Section 4.6, it, and other pre-processing methods may improve the performance assessment results.

5.5 Implementation of oscillation detection

The oscillation detection algorithm is developed according to Section 4.7. At every sampling instant, the index calculation process starts by checking the sign of the error signal. If the sign is the same as it was in the previous sampling time, which means that no zero crossing occurs, the IAE value is continued to be calculated with Equation (51). Every time the error value changes from negative to positive or from positive to negative, the accumulated IAE value is compared to the IAE limit value calculated using Equation (53). After this, the IAE value is reset.

The $load$ value indicates the load disturbance occurrences. If the IAE value exceeds the calculated IAE_{lim}, a load disturbance is detected, and $load = 1$. If the IAE value is not above the limit $load$ is set to zero. During the IAE value calculation, when the error sign stays the same, $load$ is zero.

The resulting $load$ value is used to calculate a weighted sum of the load disturbance occurrences per Equation (54). By using the weighted sum, the oscillation detection algorithm in effect resets itself after a time period. If no load disturbances are detected the sum gets smaller at every time step, and finally decreases to zero. If the sum of the load disturbances exceeds the defined limit n_{lim}, an oscillation is detected, and the oscillation detection value is set to one. This resets the weighted sum calculation.

The weighting parameter γ in Equation (54) was advised to be chosen in a way that corresponds to a sufficient supervision time. The value is scaled by a factor of thousand due to integer computation. During implementation and verification of the index it was noticed that a γ value based on the controller integral time resulted in varying efficiency in oscillation detection, when the control parameters were changed. To reach a more uniform oscillation detection, γ was given directly in the calculation. This way, it can be modified for each controller based on how fast or slow the weighted sum in Equation (54) is wanted to be updated, and thus determining the sensitivity of the oscillation detection. An initial value of 998 was given, which resulted in a slower decrease of the sum, and thus quicker oscillation detection.

It is beneficial to keep the oscillation detection value at one as long as the oscillation continues. This way, it would not be necessary to wait for the accumulated sum to exceed the limit to see whether the oscillation continues. This issue was considered in the implementation. After the oscillation detection value is set to one the next $load$ value is checked. If the value of the load indicates that another load disturbance has occurred right after the oscillation has been detected, the value for the oscillation detection is kept at one. If no load disturbance is detected, the oscillation value returns to zero.

The detection depends on the configuration parameters, and they can be modified based on how strict the oscillation detection needs to be. If wider oscillations need to be detected, the γ value can be increased. By changing the limit value, the amount of acceptable oscillations can be modified, and by modifying the oscillation amplitude limit value, the acceptable amplitude can be determined.

5.6 Index functionality validation

The indices were validated with the process model given in Equation (56). A reference signal was varied in multiple steps, both up and down. The application sample time h was set to 100 ms. Thus, it was also the time resolution. The index configuration parameters are presented in Table 4. These were chosen based on the theory, and on the tests made during the implementation phase.

Table 4. *Index calculation configuration parameters for verification tests.*

Parameter	Value
T_{sup}	2000
γ	998
n_{lim}	10
a	1
h	100

The index results are presented in Table 5 for five discrete PID controller tunings. To validate the index functionality, ranges for the index values are given for the whole simulation. From them, it can be seen whether the indices were reacting correctly to the varying controller parameters.

Table 5. *Index calculation validation with different controller parameters. Note that the controller parameters are not the standard PID-gains, but the ones applied in integer computations in WSDE.*

	$K_p = 5000$ $K_i = 2$ $K_d = 10000$	$K_p = 1000$ $K_i = 3$ $K_d = 10000$	$K_p = 16000$ $K_i = 7$ $K_d = 10000$	$K_p = 10000$ $K_i = 6$ $K_d = 10000$	$K_p = 16000$ $K_i = 16$ $K_d = 10000$
Rise time	24300… 27100 ms	10000… 11200 ms	2500…2700 ms	3700…4000 ms	1900…3200 ms
Settling time	27800… 54900 ms	10700… 26800 ms	9100… 17800 ms	4200… 13400 ms	52600…∞ ms
Estimated delay	1200…1500 ms	1200…1900 ms	1200…1300 ms	1200…1400 ms	100…1200 ms
Overshoot	0 %	0…1 %	1…32 %	1…10 %	1…80 %
Dimensionless ST	185…457	56…223	70…148	35…113	641…9930
Dimensionless IAE	66…82	35…55	24…26	24…28	48…1194
Combined step response index	1	0	-1	-1/-2	2
Idle index	-23…776	531…974	-872…-343	-352…165	-
Oscillation detection	0	0	0	0	1

The first control result is presented in Figure 11. The controller was tuned quite conservatively. There is no overshoot, and the settling and rise times are quite long. Also, the calculated index values indicate, that the control is quite slow. The combined step response index value is one, indicating sluggish control result. The idle index reaches values close to 1000, which also supports the assessment of sluggish control.

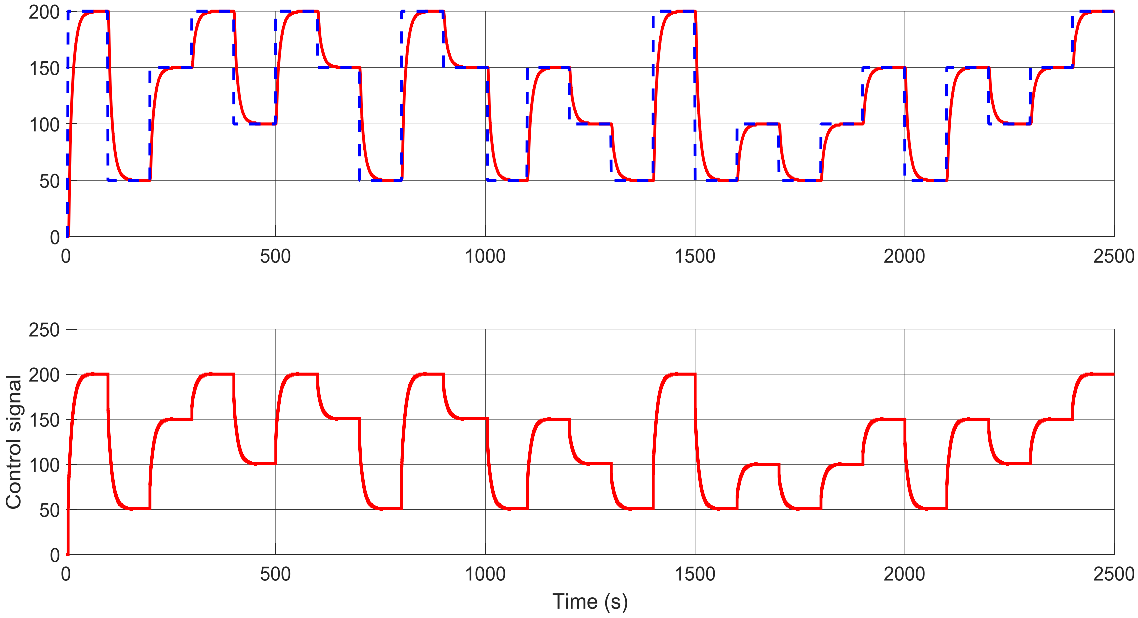

Figure 11. *Control result with controller parameters:* $K_p = 5000$, $K_i = 2$, $K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The second controller tuning result is presented in Figure 12. Compared to the first plots, the control seems to be a slightly quicker. This can also be concluded from the smaller rise and settling times. The combined index value is also indicating a better control result, because the values do not exceed the sluggish control limits, resulting in the index value being zero. The maximum overshoot for the second test is one percent. The idle index values are closer to 1000 for this test than for the first one, which indicates that the control result is still quite sluggish.

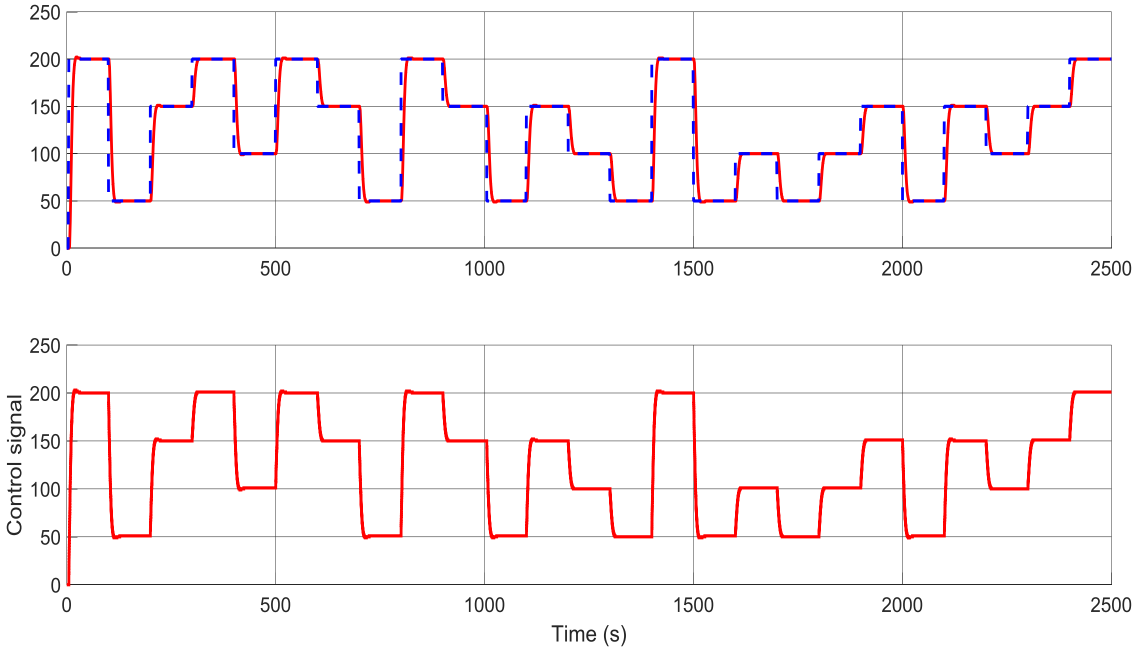

Figure 12. *Control result with controller parameters:* $K_p = 1000$*,* $K_i = 3$*,* $K_d = 10000$*. Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The third controller tuning was more aggressive, as can be seen from Figure 13. This results in smaller rise and settling times. The combined index value indicates that the control result is acceptable, because the dimensionless IAE value is under the high performance limit. The maximum overshoot is 32 percent, which is much larger than for the first control results. The idle index indicates that the control is not sluggish, giving negative values close to -1000.

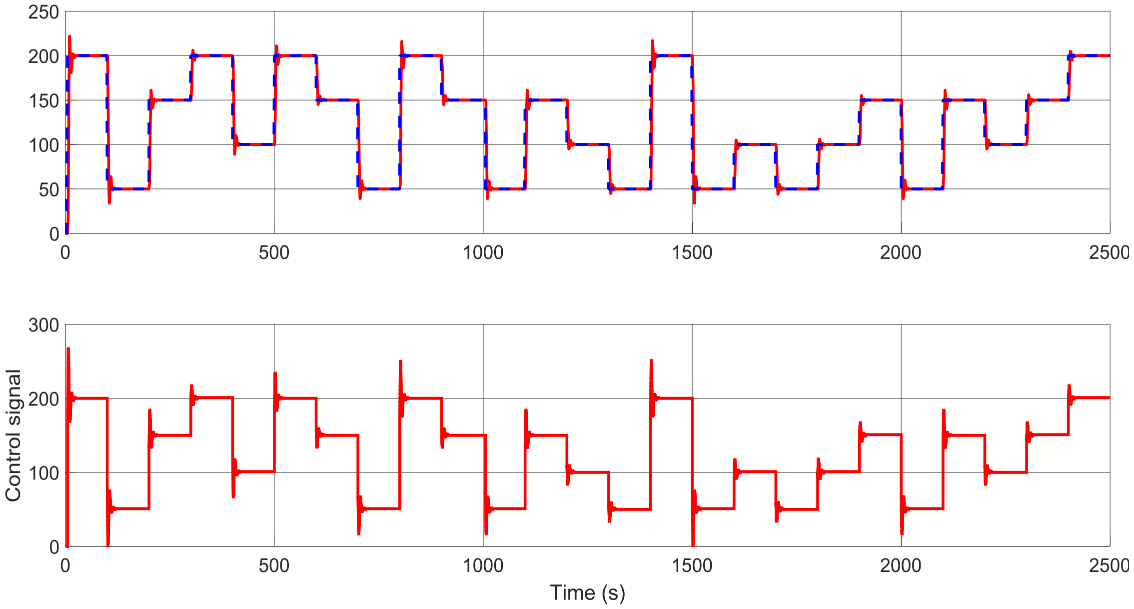

Figure 13. *Control result with controller parameters:* $K_p = 16000$, $K_i = 7$, $K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The control result with the parameters in column five is presented in Figure 14. The overshoot appears less than with the previous tuning, which is in accordance with the performance assessment algorithm that gives a maximum overshoot of 10 %. The combined index value indicates that the control is high performing in some periods. This is due to smaller dimensionless settling time and overshoot. The rise time is slightly higher than with the tuning of column four. The idle index indicates well-tuned control, giving both small positive and small negative values.

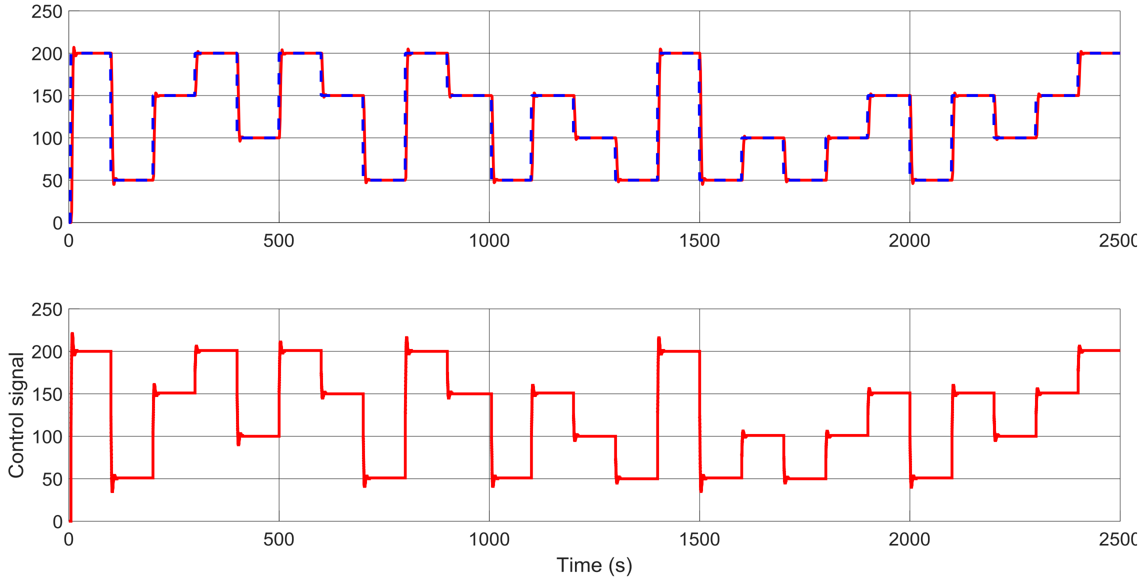

Figure 14. *Control result with controller parameters:* $K_p = 10000$, $K_i = 6$, $K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

For the last test, the integral time was increased, producing oscillatory control, see Figure 15. The rise times for this controller tuning are the smallest, but in some of the step-changes, the values do not settle before the next step-change. The overshoot maximum is

80 percent. The combined index value indicates poor control result. Oscillation is detected, and therefore the idle index is not calculated.

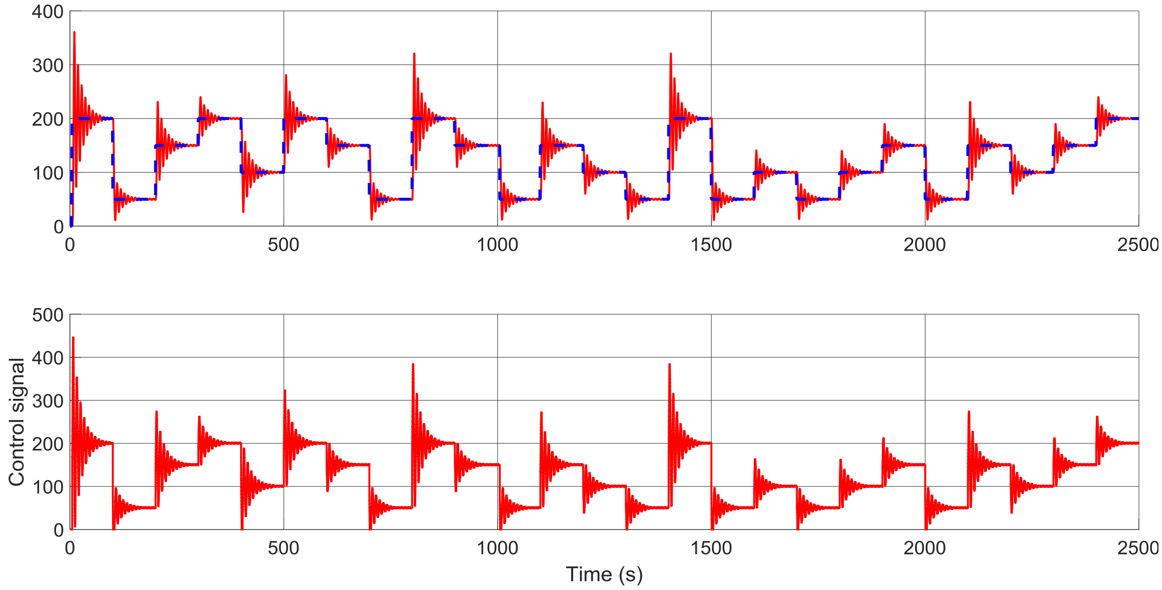

Figure 15. *Control result with controller parameters:* $K_p = 16000$*,* $K_i = 16$*,* $K_d = 10000$*. Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The correct value of delay is 1000 ms and depends only on the process. The estimated delay in Table 4 varies between 100 ms and 1900 ms, indicating, that the method should be made more accurate, as it should not change when only tuning is changed. However, the delay estimate appears sufficiently accurate when the controller tuning was assessed to be good. The deviations from true delay were largest with the poorly tuned, oscillating control. However, in the case oscillatory control the accuracy of delay is not of importance, because the dimensionless index values, depending on delay estimate, are not the most important performance indicators.

For verifying the idle index calculation during load disturbances, additional tests were made. A disturbance was added to the measurement, and the set-point was kept constant. The same PID controller was tuned with the same parameter sets as in Table 5. The idle index was computed, see Table 6.

Table 6. *Idle index results due to load disturbances with different PID parameters.*

	$K_p = 5000$ $K_i = 2$ $K_d = 10000$	$K_p = 1000$ $K_i = 3$ $K_d = 10000$	$K_p = 16000$ $K_i = 7$ $K_d = 10000$	$K_p = 10000$ $K_i = 6$ $K_d = 10000$	$K_p = 16000$ $K_i = 16$ $K_d = 10000$
Idle index, disturbance down	290	939	-436	-53	-
Idle index, disturbance up	119	851	-189	66	-

The control result with the parameters in the first column is presented in Figure 16. The idle index results for both load disturbance occurrences are given. The results do not indicate clear sluggish control.

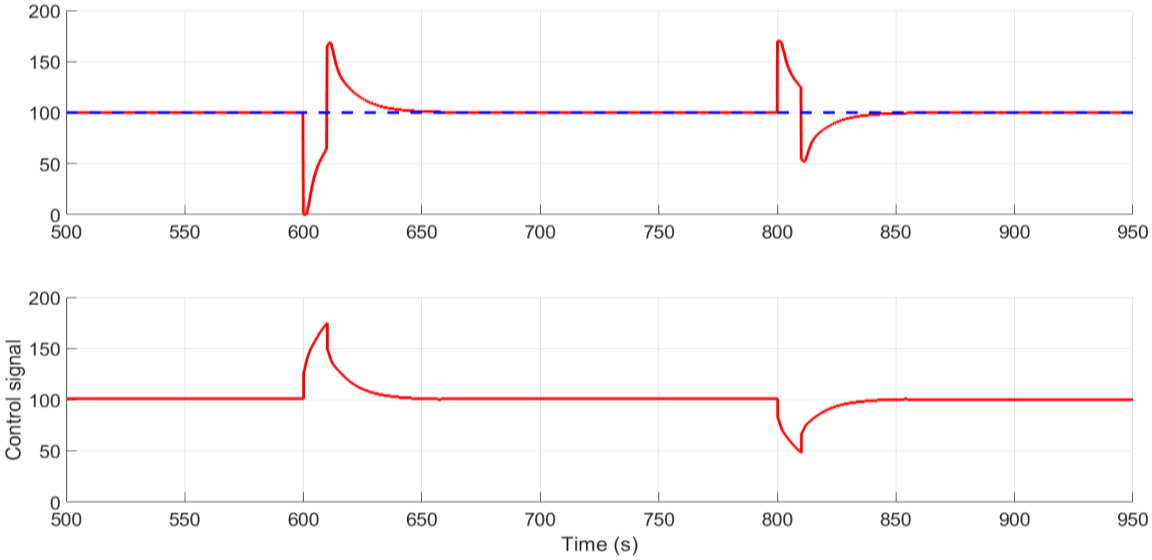

Figure 16. *Control result with controller parameters:* $K_p = 5000$, $K_i = 2$, $K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The control result for the second tuning parameters is presented in Figure 17. The idle index indicates that the control is sluggish, giving values close to 1000 during both disturbances. When comparing the first two control signals, it can be seen, that for the first one, the control is more aggressive in the beginning, but after this, it becomes slower, and it takes longer for the measurement to recover.

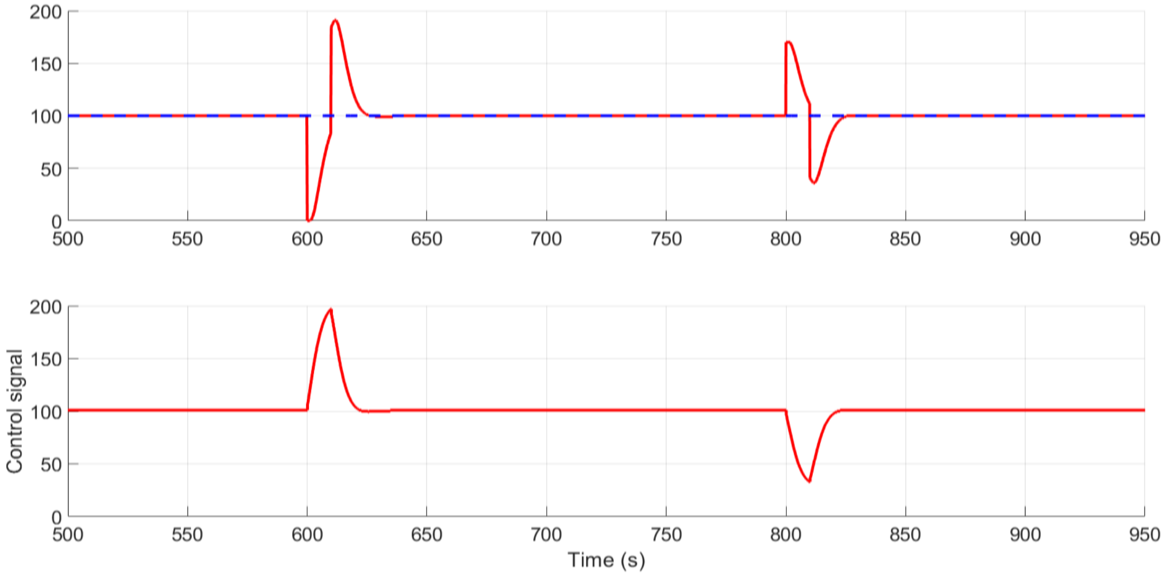

Figure 17. *Control result with controller parameters:* $K_p = 100, K_i = 3, K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The third control result can be seen in Figure 18. The controller reacts more aggressively to the changing measurement value. This is also indicated by the idle index value, which indicates well-tuned control.

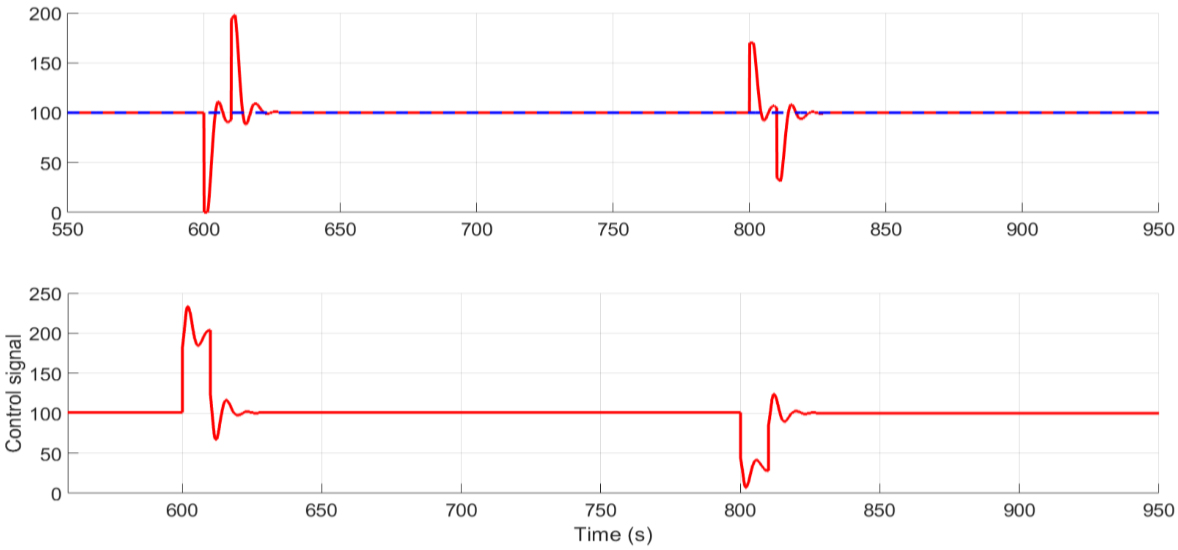

Figure 18. *Control result with controller parameters:* $K_p = 16000, K_i = 7, K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The control result corresponding to the control parameters in column four is presented in Figure 19. The control result appears also quite aggressive with the chosen PID parameters. The control and measurement signals also deviate less than in the previous case. The idle index gives values close to zero, which indicates that the controller is tuned well.

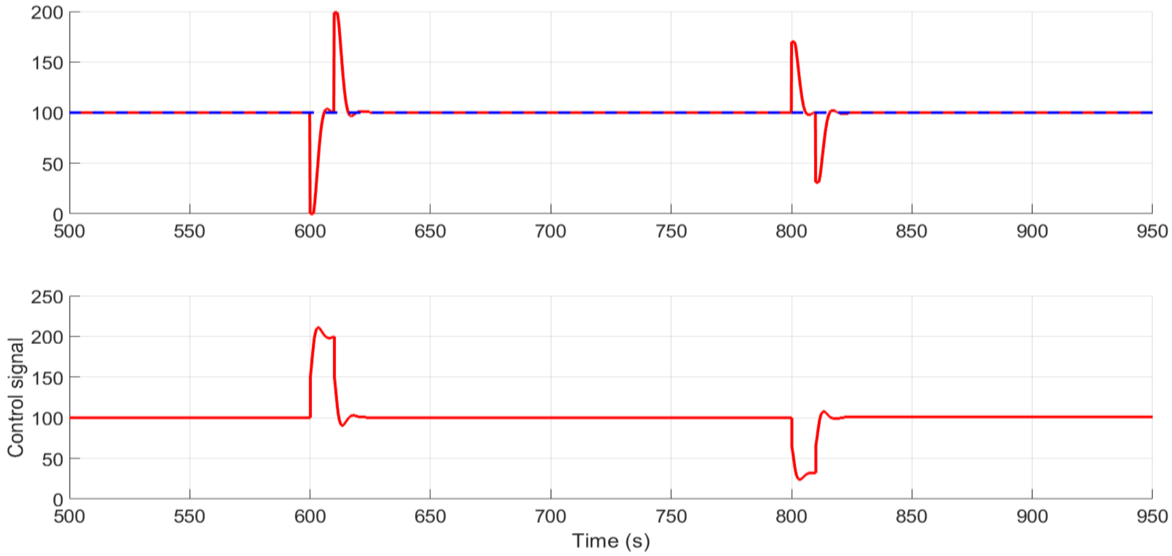

Figure 19. *Control result with controller parameters:* $K_p = 10000, K_i = 6, K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

In the last test the control was tuned oscillating. The result is presented in Figure 15. No idle index value was detected, because the oscillations correctly detected reset the idle index calculation.

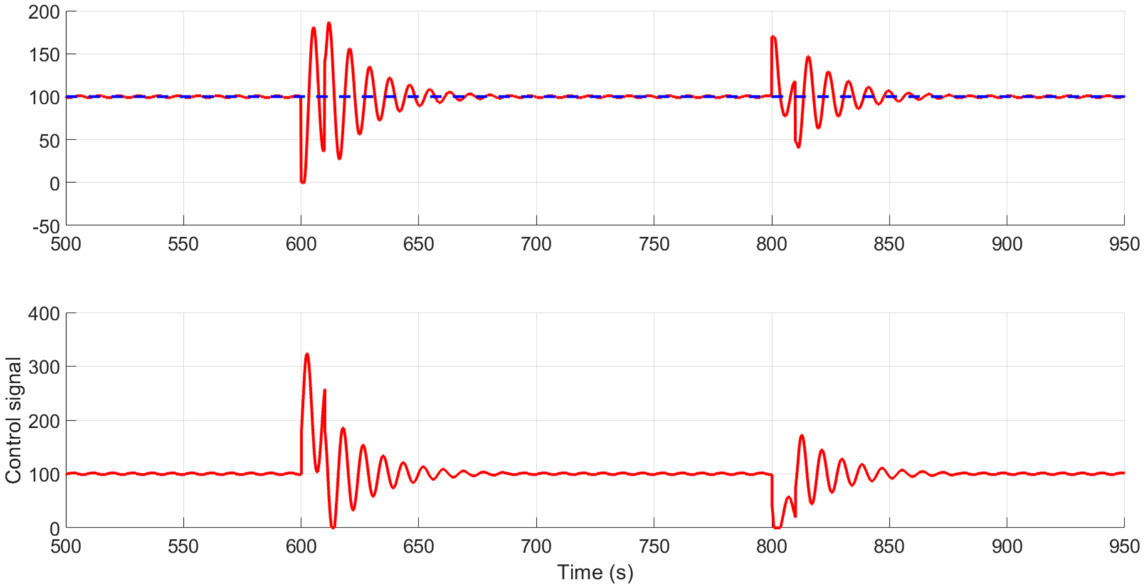

Figure 20. *Control result with controller parameters:* $K_p = 16000, K_i = 16, K_d = 10000$. *Upper plot presents the measurement in red and the reference with blue dashed line. The bottom plot is the control signal.*

The idle index seems to be giving accurate results in both steady-state and load disturbance situations. For the more sluggishly tuned control, it gives positive values, and for the faster control tunings the values are close to zero, or negative. However, the magnitude, and thus the reliability of the index. In some cases, the index clearly indicates sluggish control by being close to 1000, whereas in other cases it produces a less clear assessment of the control performance.

A possible explanation for the behaviour of the idle index is that when in the case of the first tuning, Figure 16, the control and measurement value decrease is very slow, the correlation is calculated to be zero. This is because the correlation is based on the signal increments, and the signal varies so slowly, that no change in the signals is detected between two consecutive time steps. This is due to the calculation needing to be performed in integers, and thus if the change is smaller than one it is not detected.

From the tests it can be concluded that the index algorithms perform well at indicating the control performance for the studied PID tunings. The combined index indicates how well the controller reacts to a stepwise changing reference value. The settling time, rise time and overshoot are useful when comparing the different controller tunings. These values help to decide whether the tuning becomes faster and more accurate when changing the PID parameters, or if the performance decreases. The oscillations were detected accurately, and the idle index assessed the performance in both disturbance and step change situations.

6. INDEX EVALUATION

Even though the functionality of the performance assessment tool is already verified and roughly validated when applied to a simple process model, it is important to understand, that a real process has many factors that affect the control performance, and the performance assessment. Therefore, the performance assessment algorithms need to be tested in evaluating the control performance of the actual engine processes.

The performance assessment algorithm is first evaluated using an engine Simulink simulator model. This allows assessing the performance in different system states, and tuning parameters can be varied freely to generate different control performance. The model can give a good indication on how well the developed methods work in assessing the control performance, and based on the tests the algorithms can be further developed to suit the evaluation of the engine processes specifically.

The Simulink model consists of submodels for the engine processes and their control loops. The index algorithms are integrated to the gas pressure and the speed PID controllers. However, a model is never capable in accurately portraying the actual process. For this reason, the performance assessment methods need to be evaluated in the actual engine system as well.

In this Chapter, integrating the performance assessment to the PID controllers is first explained. Then, the results using the engine Simulink model and the actual engine are presented. Finally, the indices as an aid in tuning is discussed.

6.1 Setup

The performance assessment algorithms are included in the Simulink implementations of the applications. The calculation is included in the software package next to the PID controllers in both speed load control and the gas pressure control. The same calculation subsystems can be utilized in both of the applications, which makes the calculation easily generalizable to different control loops.

Integrating the performance calculation to the PID controllers is relatively straight forward. The measurement, reference and control signals, as well as the proportional and integral gains are connected from the application PID controller to the performance assessment calculation. The upper level of the Simulink model of the assessment algorithm is presented in Figure 21. As can be seen, the signals from the PID can be simply connected to the Simulink subsystem “Collect signals”.

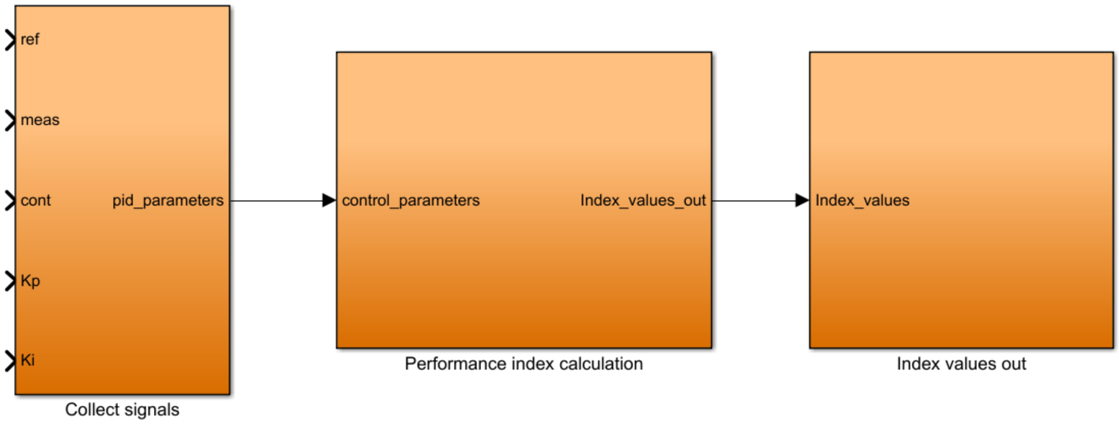

Figure 21. *Performance index calculation implementation overview.*

The control error is calculated inside the “Collect signals” block. The “Collect signals” block is presented in Figure 22. It simply gathers all the signals in one bus, and feeds them to the performance calculation block.

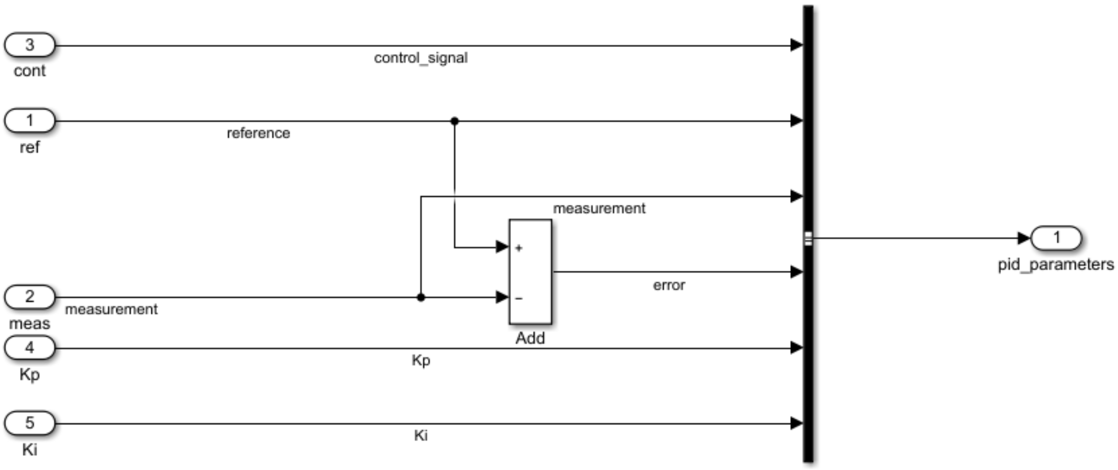

Figure 22. *Performance index calculation collect signals block.*

The performance index calculation subsystem is presented in Figure 23. It is divided into the idle index calculation, oscillation detection calculation and step response based index calculation. Inside these blocks, the calculation is done as described in Sections 5.3, 5.4 and 5.5.

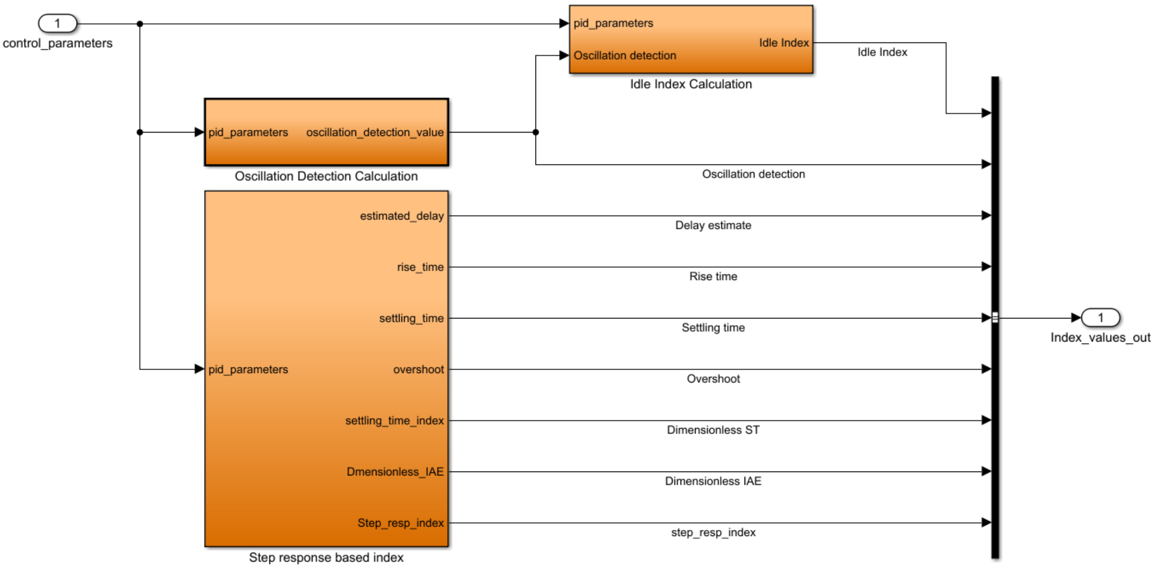

Figure 23. *Performance index calculation subsystems.*

The outputs from the performance index calculation are the Idle index, oscillation detection value, delay estimate, rise time, settling time, overshoot, dimensionless settling time and IAE, and the combined step response index. All of these can be calculated online, and the control performance can be assessed during the engine operation.

The structure of the index calculation makes it easy to implement to any PID controller. This is an important advantage, as it does not take too much time to add the calculation to the applications.

6.2 Index calculation tests with engine Simulink model

Before testing the index functionality and usefulness in an actual engine, the indices were tested in a Simulink model of an engine, using gas as its main fuel. The model consists of the engine model and the control applications for each process.

The process model is a rather crude model of the engine functionality. The real process differs from this, and thus the results gathered from these tests do not describe fully and accurately the real engine control performance. However, they do give indication on how well the indices work in assessing the engine control performance, and how the results differ between the controllable processes.

6.2.1 Speed control performance assessment

In the speed control application the sample time is 10 ms. The index configuration parameters are presented in Table 7. The performance assessment sample time is set to 10 ms to match the control update rate. The limit for acceptable oscillations is set to three, in order to detect oscillations quicker.

Table 7. *Speed control performance assessment configuration values.*

Parameter	Value
T_{sup}	2000
γ	998
n_{lim}	3
a	1
h	10

The speed control performance is assessed for the control results in Figure 24. The upper plot presents the control signal from the speed control, and the bottom plots are the measured speed and speed reference.

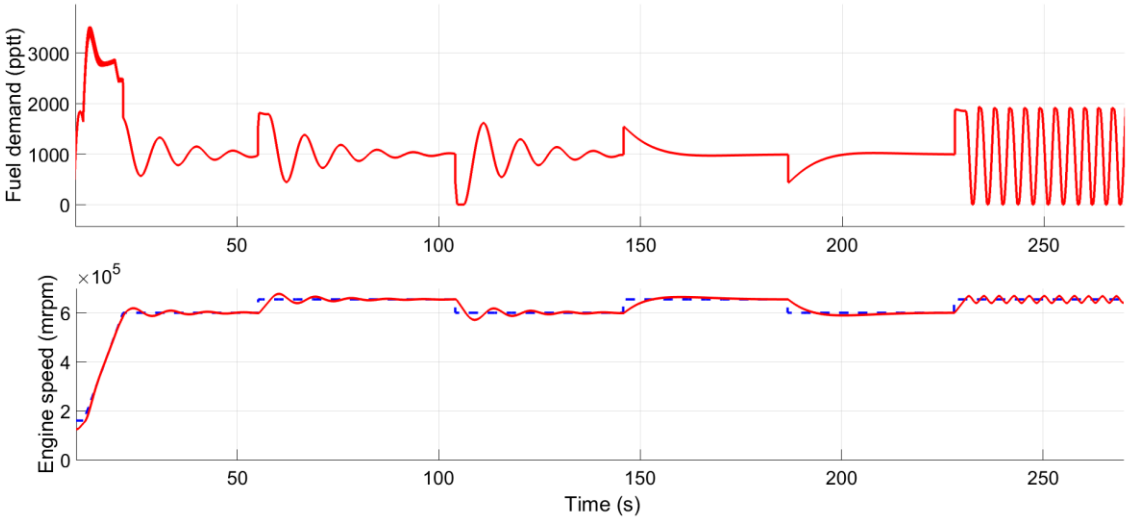

Figure 24. *Speed control signals. Upper plot presents the control signal, and below is the measured speed in red and speed reference with blue dashed line.*

First, the engine was started with default PID parameters. After the measurement had settled the speed reference was raised stepwise from 600 rpm to 655 rpm. After this new value had settled, the speed reference was brought back to 600 rpm. For the next step increase from 600 rpm to 655 rpm, the integral gain was decreased to five percent of the original value, thus increasing the integration time, with the aim of reaching worse control result. The same control parameters were kept when the speed was decreased from 655 rpm back to 600 rpm. The final test was made to test oscillation detection. The integral gain was increased to seven times the original value, to make the controller oscillate. The resulting oscillation can be clearly seen in the measurement plot after approximately 235 seconds.

The results in Table 8 represent the performance assessment during different stages of the test. The settling time t_s, rise time t_r, estimated delay d, overshoot, idle index and oscillation detection are given. The dimensionless index values and the combined step response index are not shown. This is because the estimated delay was zero, in which case the dimensionless values cannot be calculated.

Table 8. *Speed control performance assessment results during different states of the process.*

	Initial ramp up	Step up	Step down	Low I-gain, up	Low I-gain, down	High I-gain
t_s (ms)	-	19370	19860	21050	22440	-
t_r (ms)	-	2920	2450	6560	6230	2600
d (ms)	0	0	0	0	0	0
Overshoot %	3	3	4	1	1	2
Idle index	-	143	169	-833	-833	-
Oscillation detection	1	0	0	0	0	1

For the initial ramping up of the values no settling time or rise time can be determined with the established methods. The overshoot value gives the correct deviation from the set point once the reference value has settled. Oscillation is detected, because the reference and measurement signals overlap during the ramp up process.

Settling and rise times indicate the effect of the control parameters to the control performance. Decreasing the I-gain doubles the rise time and clearly increases the settling time.

The idle index value indicates that the control for the two first steps is well tuned, and that the control perfromance is good for the slower tuned controllers as well. From Figure 24, it can be seen, that the correlation between the rate of change in the measurement and control signals is in fact negative for a long time, thus explaining the large negative idle index value. This can be further explained by the control signal, which has a fast initial response to the changing set point, and then decreases to the required level. This would suggest that the controller should be tuned even slower, in order for the control result to be sluggish, at least by the idle index standards.

The oscillation detection value succeeds in correctly indicating when an oscillation is present. However, it was noticed, that the configuration parameters need to be modified based on the application, and on how strict the oscillation detection needs to be. Here, the limit of acceptable oscillations was set to three, and it seemed to work well for detection of oscillations in the speed control. Furthermore, the acceptable amplitude should be set based on how much the values are allowed to deviate from the set point.

As the delay was estimated to be zero, the dimensionless values were not calculated. This is a clear limitation of the dimensionless indices. The zero delay value may be due to the model inaccuracy, or result from the delay evaluation calculation being too simple. As was noticed with the tests done in Chapter 5, the estimation is not very accurate, and thus when moving to assess the actual processes this was even more clearly noticeable.

6.2.2 Gas pressure control performance assessment

The performance of the gas pressure control is assessed based on the control results in Figure 25. Mostly the same index configuration values were used as in Table 7, with the exception that the limit of acceptable oscillations was increased to five.

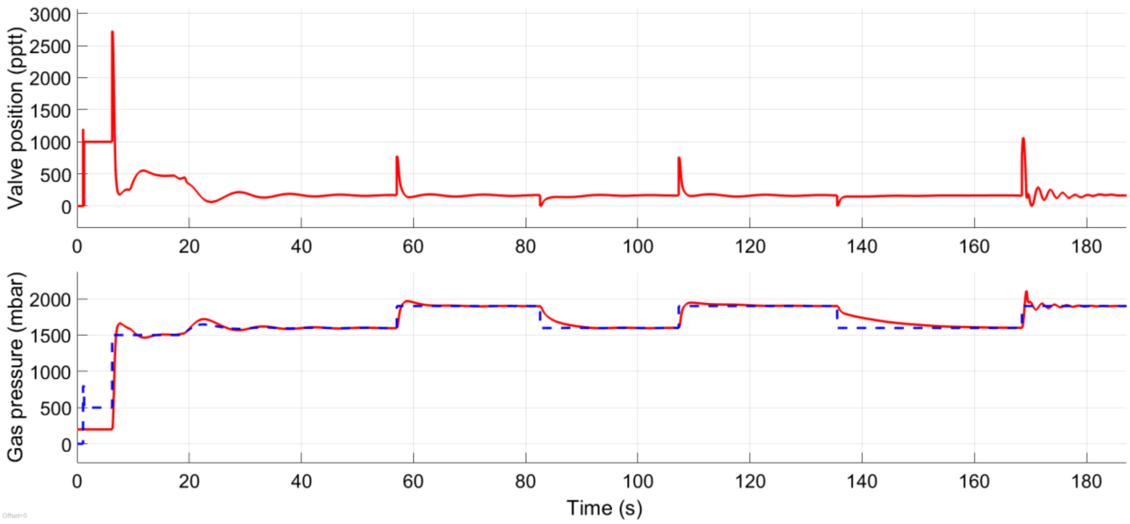

Figure 25. *Gas pressure control signals. Upper plot presents the control signal, and below are the measured speed in red and speed reference with blue dashed line.*

First, the default gains and set point were used to increase the pressure during the engine start. After the value had settled, the pressure reference was increased from 1600 mbar to 1900 mbar. After this had settled, the pressure reference was decreased back to the initial level of 1600 mbar. For the next step up, the integral gain value was decreased to 40 % of the initial value to make the control slower. The reference was decreased back to 1600 mbar after the slow response had settled. Finally, the integral gain was increased to over ten times the original value, to reach oscillating control.

The performance parameters for the simulation tests are given in Table 9. The index values for each step change are presented in their own columns. In the first data column the index values for the initial step-change are presented. According to the combined step-response index, the control result is sluggish. However, as can be seen from Figure 25, the controller reacts aggressively to the changing set point, and thus this detection is false. This is due to the small estimated delay value, which makes the dimensionless values significantly larger than the limits for poor control. However, the idle index assesses the controller to be well-tuned, which seems more accurate.

Table 9. *Gas pressure control performance assessment results.*

	Initial up	Step up	Step down	Low I-gain, up	Low I-gain, down	High I-gain
t_s (ms)	23290	4770	5410	10110	20960	5930
t_r (ms)	630	740	770	840	5200	450
d (ms)	10	20	40	10	20	10
Overshoot %	10	3	-	2	-	11
T_s	> 133	> 133	> 133	> 133	> 133	> 133
IAE_d	> 63	> 63	> 63	> 63	> 63	> 63
Combined step-resp. index	1	1	1	1	1	2
Idle index	-667	-146	-428	-313	-337	-
Oscillation detection	0	0	0	0	0	1

After the initial gas pressure has settled, the pressure is increased with a step (second data column). The estimated delay is still very small, and thus the combined index value cannot be relied on. The rise time is higher than for the initial step, but the value settles much quicker. The step down in column third data column has a longer rise and settling time than the step up, even though the controller parameters are not changed. Based on the idle index value, the control result is good during both steps.

For the next two columns the integral gain is decreased. For both the step up and step down the rise and settling times are higher than the corresponding values using the initial integral gain, data columns two and three. However, based on the idle index, the control is not sluggish.

The last column presents the results for the oscillating control, with the limit of acceptable oscillations set to five. The rise time is short, because the integral gain is increased. The overshoot is 11 %, at its highest in this test, as would be expected. The combined index value is two, indicating poor control performance.

6.2.3 Performance index evaluation based on Simulink tests

During the tests on an engine Simulink model, a couple of general problems arose. First, the estimated delay values were very small, which makes the dimensionless performance assessment difficult. The values are either not calculated, because the estimated delay is zero, or the delay is so small compared to the settling time, that the dimensionless values are way beyond the poor performance criteria. This may be due to the simulation model not being accurate enough in describing the system delays, and also due to the simple delay estimation calculation. As mentioned before, the accuracy of the delay estimation algorithm needs to be improved.

The reference values are calculated during engine operation, and the changes are not always step like. When starting up the engine, some of the reference values are ramped up, which makes the performance assessment more difficult, because the step-change based indices cannot be estimated with the presented procedure.

The limit of ten acceptable oscillations was too high in most cases. Because the load disturbance sum decreases during the IAE value calculation, when load is zero, the sum decreases significantly if the oscillation frequency is high. Because of this, it takes a long time to reach the limit of ten load disturbances. Modifying the value to be five or less, made the detection of oscillations much faster and meaningful from the application perspective.

There was a lot of information provided by the indices. The settling time, rise time, estimated delay and overshoot values did provide useful information if the control performance improved or degraded because of change in tuning. They also indicated that the rising step was more quickly reached than the falling step, indicating system nonlinearity. However, the delay estimation did not provide useful results, due to model inaccuracy and the algorithm being too simple.

It can be argued whether the idle index is suitable in assessing the performance of these controllers. It seems, that even though the control parameters are tuned to be slower, the time of the positive correlation is still really small. This results from the fast control action right at the beginning, after which the controller slowly corrects itself to the appropriate value. This only results in long negative correlation, thus the idle index interprets this as well-tuned control. It might help to have both long positive and negative correlation to be detected as sluggish control. This way, the slowness of the control would be indicated in both cases. However, the idle index is mainly developed for assessing the performance during sudden load disturbances, and thus may not be ideally suited for set-point changes.

6.3 Index calculation during engine operation

The final tests were made on a Wärtsilä laboratory engine. The tests were similar to the ones with the Simulink engine model. The engine did not contain the speed load control, and therefore the tests were conducted only on the gas pressure control application. No index configuration values were changed during the tests. The values used are given in Table 8.

Table 10. *Gas pressure control performance assessment configuration parameters.*

Parameter	Value
T_{sup}	2000
γ	998
n_{lim}	5
a	1
h	10

The index calculation was included in the gas pressure control application according to Section 6.1. After adding the calculation to the application, C-code was generated from the Simulink implementation and added to the engine control software package. This software was then downloaded to the engine.

6.3.1 Gas pressure control performance assessment

The performance assessment functionality was tested during engine operation under three circumstances. First, the gas pressure PID controller with default gains was assessed during load steps. For the second test, the controller integral gain was decreased to one third of the previous value, resulting in a slower response. For the final test, the controller integral gain was doubled resulting in oscillations.

The gas pressure reference were changed by changing the engine load reference value. First, the engine load was 150 kW, from which it was increased to 300 kW, and once the values had settled, it was returned back to the initial level of 150 kW. Because the gas pressure reference is dependent on the current engine load value, it changed as the result of changing the engine load. This procedure was used in the first two tests.

Figure 26 presents the gas pressure control signal, measurement, and reference values during load steps in the first test with initial PID parameters. As a result to increasing the engine load, the gas pressure reference increased, and in turn, when the load value was decreased, the gas pressure reference decreased as well. It can be seen, that the reference does not change with a clear step, but rather ramps up quite slowly. This causes issues with the index calculations, as some of them are developed for situations when the set-point change is step like.

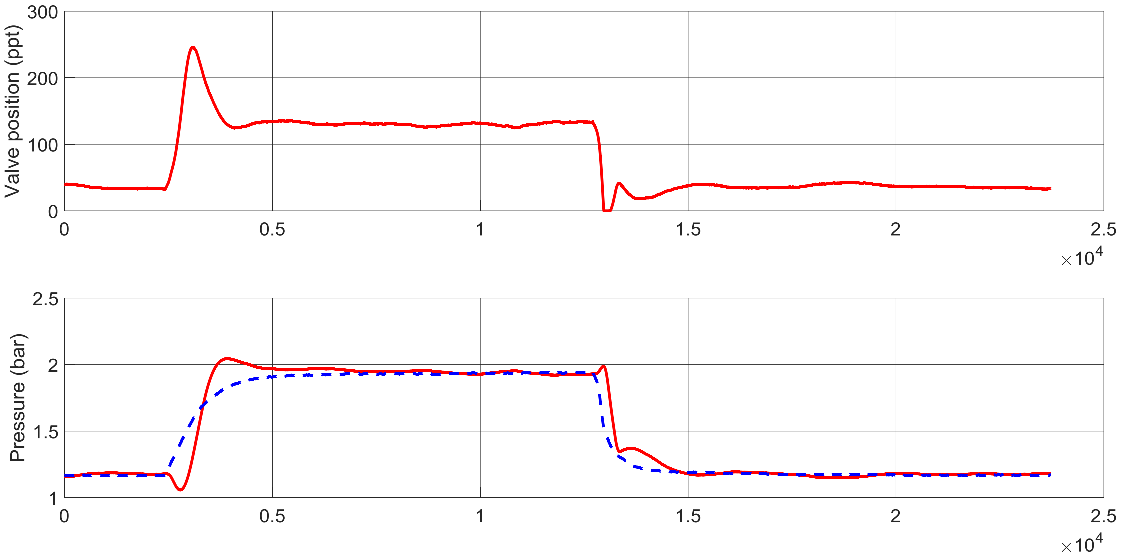

Figure 26. *Gas pressure control signals with no change made to the control parameters. Upper plot is the control signal, and bottom plot depicts the reference value with blue dashed line, and measurement with red solid line.*

The resulting idle index from the first test is given in Figure 27. It indicates, that the control performance during the step changes is not sluggish, as the values stay close to zero for the whole simulation.

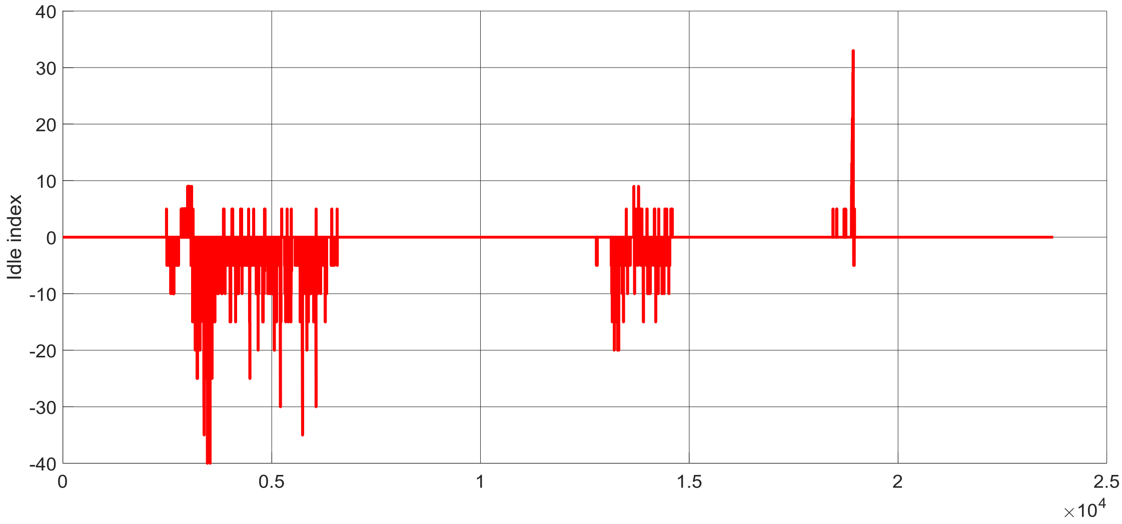

Figure 27. *Gas pressure control idle index value, no changes made to the control signals.*

The oscillation detection result from the first test is presented if Figure 28. It indicates that oscillation is present before the first step, after the first step, and also after the second step. The detected oscillation is not clearly visible from Figure 26, and with further tests it should be assessed whether or to the oscillation detection should be this sensitive to measurement deviations.

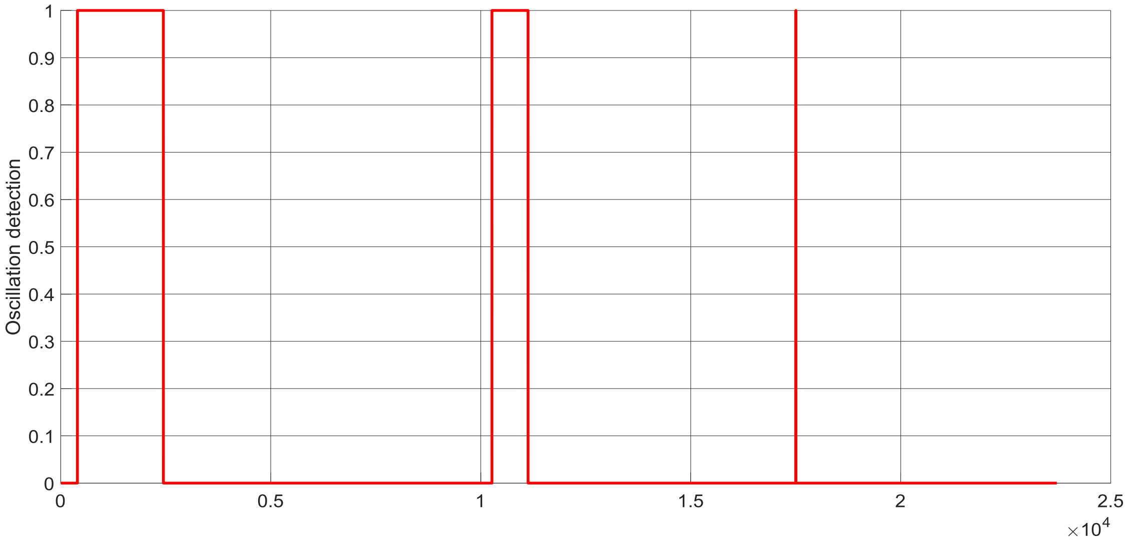

Figure 28. *Gas pressure control oscillation detection value, no changes made to the control signals.*

Even though the overshoot percentage cannot be directly defined from the signals due to the reference not being a clear step, the calculated value still provides information on the deviation from set-point, as can be seen from Figure 29. For the first step, the largest deviation from the set-point is 15 percent. For the step down, the deviation maximum value is ten percent. These do not occur during overshoot, but rather right at the start of the step-change.

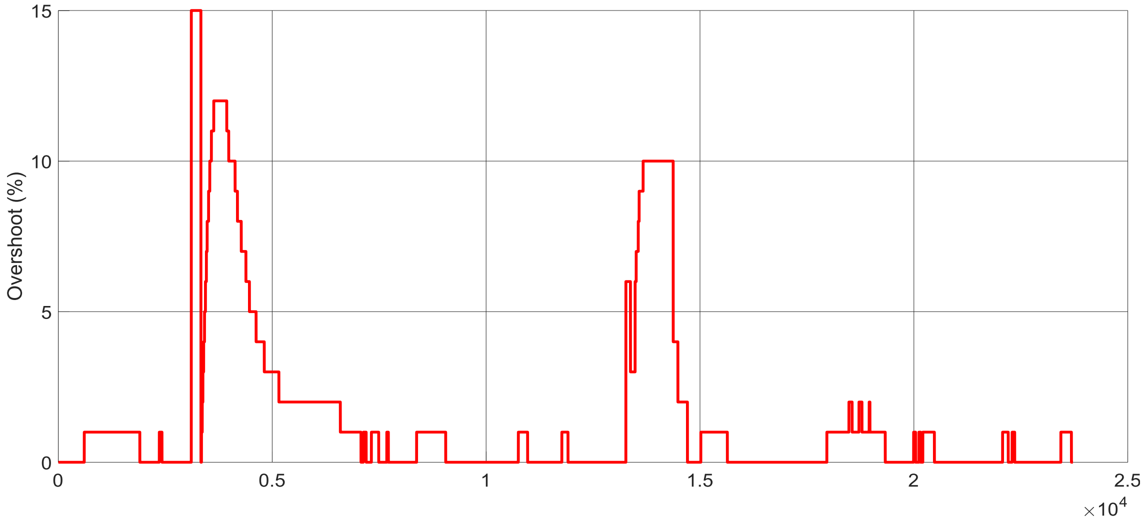

Figure 29. *Gas pressure control overshoot value, no changes made to the control signals.*

The next test was to decrease the integral gain value in order to reach a slow control response. The resulting measurement, reference and control signals are presented in Figure 30. The reference change was made the same way as for the first test, by modifying the engine load from 150 kW to 300 kW and back to 150 kW.

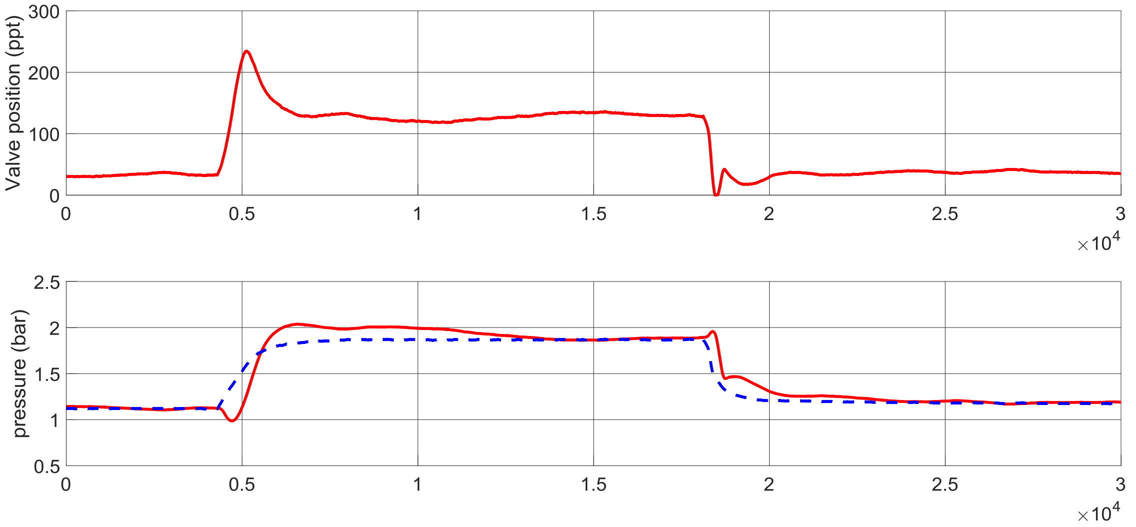

Figure 30. *Gas pressure control signals when controller tuned slower. Upper plot is the control signal, and bottom plot the reference value with blue dashed line, and measurement with red solid line.*

When comparing the result to the plots in Figure 26 with initial controller parameters, it can be seen that the control result is slower, and it takes more time to reach the reference pressure. However, the control result does not seem to be too sluggish, and the controller still reacts quite quickly to the changing reference value. The idle index for the second test is presented in Figure 31. It can be interpreted that the control result is not sluggish, because the values stay very close to zero. However, interpreting the more accurate idle index value should not be made in this time scale, because as can be seen from the Figure, it is hard to distinguish. For more accurate idle index values, each step should be inspected separately. In addition, because the control behaviour is more complex than in the cases presented in Chapter 5, and the measurement exceeds the reference value, performance assessment using the idle index becomes more difficult.

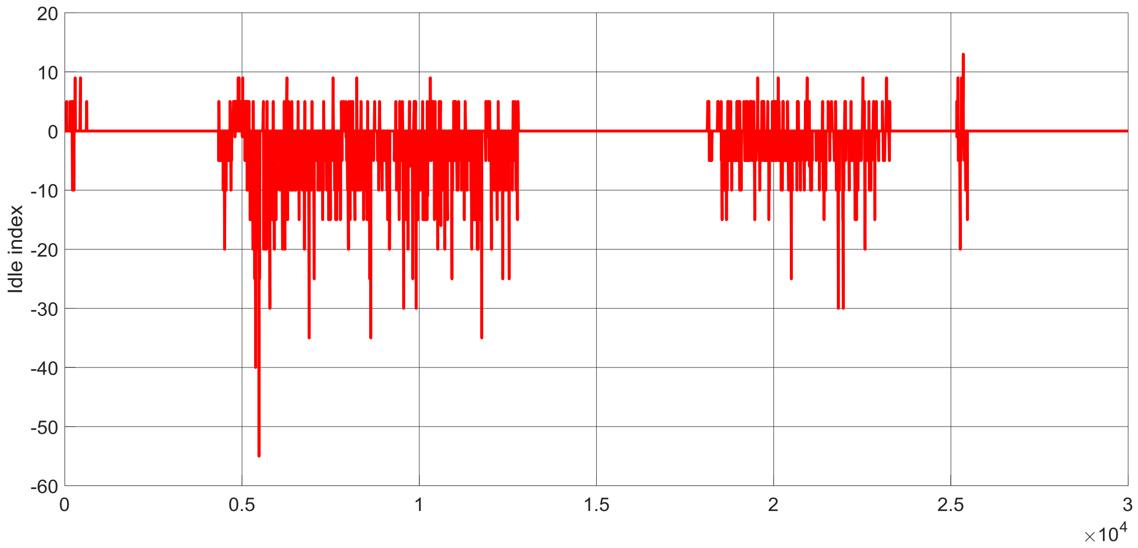

Figure 31. *Gas pressure control idle index value, controller tuned slower.*

The oscillation detection result for the second test is presented in Figure 32. According to it, oscillation is detected during the settling of both of the steps. However, it is not present for a long time, as the value is reset quite quickly. By changing the parameters used in the oscillation detection calculation it can be determined how sensitive the method is to oscillations.

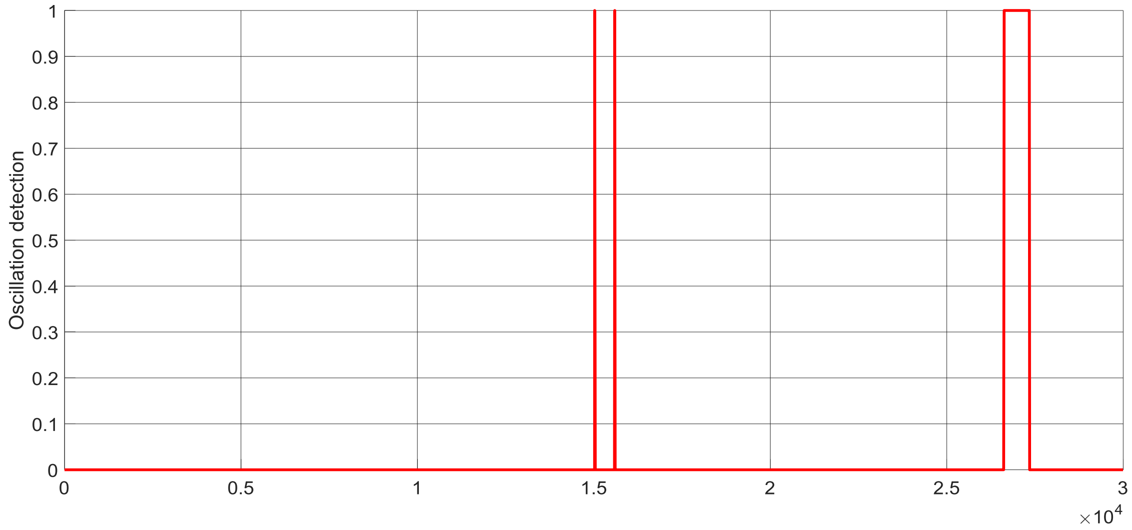

Figure 32. *Gas pressure control oscillation detection value, controller tuned slower.*

The overshoot value from the second test is presented in Figure 33. Again, because the reference change is not a step, the overshoot cannot be directly determined from these values. However, it does indicate the deviation from the set-point during the simulation. The deviation from set-point during the first step change is quite significant, 28 percent. For the second reference change the measurement deviation from set point is at its maximum at 16 percent. If comparing these values to the ones derived from the first test, in Figure 29, they are significantly bigger, and indicate a worse control performance during the second tests. This was expected, as the controller was tuned to be worse on purpose.

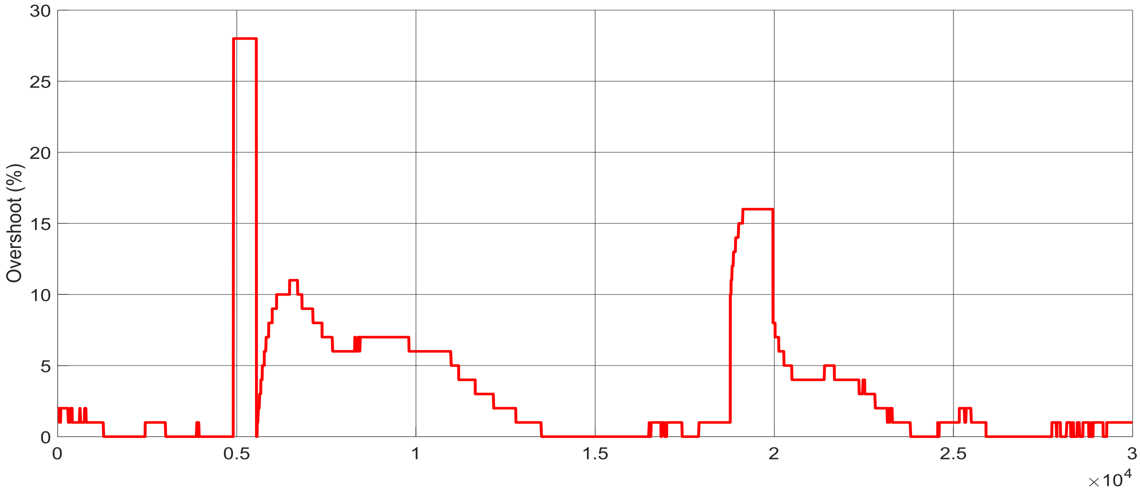

Figure 33. *Gas pressure control overshoot values, controller tuned slower.*

For the final test, the integral gain value was increased until the controller was oscillating. The resulting measurement, reference and control signal are presented in Figure 34. The integral gain was increased during the testing, which is why the oscillation amplitude is increasing towards the end. After clear oscillation was achieved, the integral gain value was slowly decreased back to a normal level.

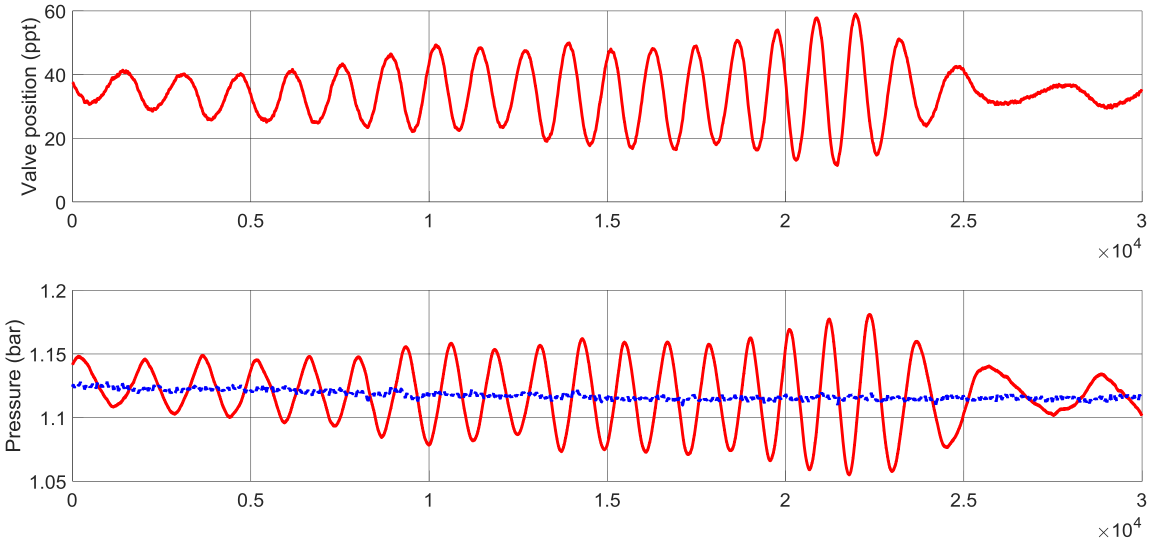

Figure 34. *Gas pressure control signals when controller tuned to be oscillating. Upper plot is the control signal, and bottom plot the reference value with blue dashed line, and measurement with red solid line.*

The oscillation detection result corresponding to the oscillating control result in Figure 34 is presented in Figure 35. It clearly indicates that oscillation is present. The first oscillation is detected quite quickly, and after that the value does go to zero occasionally, but the index still clearly indicates the oscillation. However, it would be desirable that the oscillation detection did not return to zero, when a clear oscillation can be seen in the measurement signal. The result could be improved by modifying the configuration parameters, and by improving the algorithm to keep the value at one more consistently.

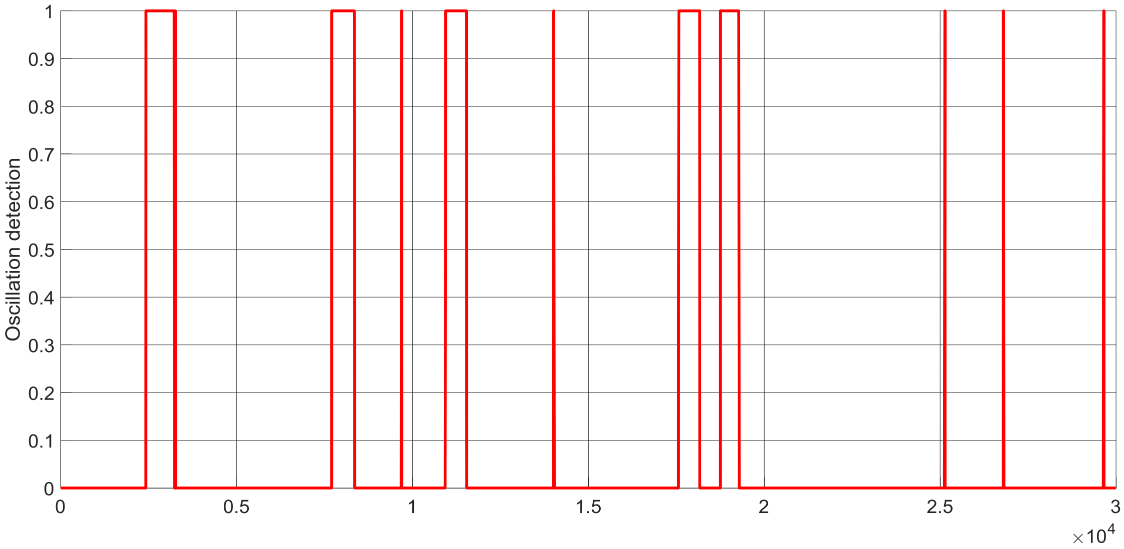

Figure 35. *Gas pressure control oscillation detection result when controller tuned to oscillate.*

For the oscillating control result, the largest deviation from the set-point according to the overshoot calculation was five percent, detected at the time the oscillation is at its largest. This indicates that the oscillation did not deviate too much from the set point value, with an amplitude of maximum five percent from reference.

The rise time, settling time and delay estimation calculation did not function correctly during the gas pressure control performance assessment. The estimated delay stayed at zero during the whole testing. Due to this, the dimensionless values were not calculated, and thus the combined step response index was also zero. Because the reference change was not stepwise, the rise time and settling times were not able to be used for the performance assessment.

6.3.2 Performance index evaluation based on engine tests

The engine tests indicated that there are things to be improved in the performance assessment calculations. The real system dynamics and behaviour need to be examined more closely, and the indices need to be modified to work based on each process and its functionality. The natural deviation in the signals needs to be considered when implementing the indices, and it should not be regarded as poor control. Because the indices were developed based on the values staying constant if no changes were made, they detected false poor control, or did not calculate the values correctly during the real life process performance assessment.

Furthermore, during the initial tests it was assumed that the reference changes are step like. However, for the real process this turned out to be not true, at least for the gas pressure control. The tests revealed that the references are ramped up, which means that the reference value changes slowly towards the end value. In these situations, the step-response based index values cannot be directly used. For this reason, the performance could really only be assessed with the oscillation detection, and idle index values.

The engine tests also further emphasized the fact that there is a need for more precise delay estimation. The algorithm developed for it in the current implementation is very simple, and this might be the reason why no delay was detected in the actual process tests. The importance of the delay value is quite significant, because if it cannot be derived, the combined step response index is zero. This significantly decreases the benefit gained from the performance assessment. However, as the combined index is also created to assess the performance of the stepwise reference change, improving the delay estimation does not improve the performance assessment results.

The idle index was calculated during the engine tests. If the controller integral gain value had been decreased even more, and the control result would have been really slow, the idle index could have provided more value. Additionally, changing the supervision time might help in getting a more clear result from the calculation. However, as the real process controls indicated, there is usually an overshoot in the signals. This makes the idle index reliable only in situations when the controller tuning is extremely slow. It should also be noted, that the main task for the idle index is to assess the performance during abrupt disturbances. Thus, the assessment during reference changes should be mostly based on other measures.

The oscillation detection provided valuable information on the control performance. However, the algorithm might have been even too sensitive to the deviations from set point. This is also due to the natural deviation of the values not being taken into account when developing the indices. Nevertheless, the oscillation value did function correctly, and by modifying the configuration parameters the sensitivity of the oscillation detection can be decreased if desired. This should be done individually for each control application, as different variations in the signals are allowed for each process.

The value provided by the overshoot calculation was also used to assess the control performance, even though it does not indicate the actual overshoot if the reference change is not stepwise. However, as could be seen, the value did provide useful information on how much the measurement deviated from the set point. This is due to the implementation of the overshoot calculation being able to assess the deviation during the whole simulation. This may be confusing, and it should be considered if the deviation should be calculated separately, and overshoot would only be indicated during stepwise set-point changes.

In general, the performance values are the most beneficial, when they can be compared to the previous values in between the tuning. By doing this, it can be seen if the control performance is improving or getting worse when the control parameters are changed. In the engine tests, it could be clearly seen that the control performance got worse when the integral gain was modified.

The performance assessment results for the engine model and the actual engine are quite different. Both tests were made using the same performance assessment configuration parameters in Table 10. It should be noted, however, that the set-point change magnitudes were different. For the model, the gas pressure was changed in between 1.5 and 1.9 bars. In the real environment, the change was much bigger, from approximately 1.2 to 2 bars. In addition, for the model, the gas pressure changes were step like, and for the actual engine they were ramped up. These explain many of the differences in the results, because the step like changes and no deviation in the measurement value make the performance assessment easier.

When using the engine model, the estimated delay was calculated, and thus it also provided the combined step response index values. In addition, the idle index value was easier to interpret when using the model of the process. The rise and settling times were correctly calculated in the model environment, because the set-point change was stepwise. The values that gave similar results were the oscillation detection, and overshoot.

These tests clearly show the significance of using the actual, real-life process, when testing the indices and their functionality. Even though the indices provided good results when testing with the actual process model, it did not guarantee that they work well on an actual process. The non-minimum phase response, in Figure 26, made it more difficult to assess the control performance with the methods developed for more simple control responses.

6.4 Computational load

Adding the performance index calculation will inevitably increase the CPU power needed in applications. Measuring the increase will indicate if the performance assessment algorithms can be fitted into the engine software package.

The CPU power required for the index calculations was tested for the gas pressure and speed load control applications. The testing was done on a rig that consists of the engine control modules, with the control software package of the Wärtsilä 31DF engine. First, the control performance assessment functionality was disabled. Then, when the engine control system was running, the CPU power needed for each application was measured. The measurement was taken every second, for 270 seconds, and the resulting data was saved. Next, the performance assessment was enabled, and the resulting CPU need was measured for both applications during 300 seconds. The measured CPU deviated during the calculations. For this reason, an average of the values was calculated. The difference between the two measurements was the power needed for the performance index calculations.

For the gas pressure control application, the average CPU usage increase was approximately six percent, and for the speed load control application the CPU increased by five percent. The gas pressure control calculation was done on a smaller set of values than the speed load control. This was due to the engine being a duel fuel engine, and during the tests it was ran on both diesel and gas modes. During diesel mode, the gas pressure control is not activated, and thus neither is the performance calculation. The gas pressure CPU calculation was performed with only the data during gas mode operation.

The amount of CPU needed can be decreased by optimizing the developed algorithms. For the current implementation, the main concern was to be able to perform the calculations correctly, and optimizing the used CPU was not the main concern.

There is no straightforward answer to whether this amount of CPU increase is acceptable. It depends on if the calculation is only done during tuning, or if the calculation is continuous. If the performance assessment is only enabled when tuning the engine control parameters, the amount of CPU required is not a major concern. However, if the calculation is to be done continuously during engine operation, the benefits that the performance assessment brings, effect on how much CPU can be allocated for the calculation.

The performance assessment can also be added to just the applications that it brings the most benefit in. This way, the required CPU for performance assessment can be decreased, and only the most critical loops can be assessed. It might be beneficial to assess the need individually for every engine package. If the software is already taking a lot of CPU, the performance assessment part might be smaller. The modularity of the developed application makes it easy to include based on the acceptable CPU usage for each engine.

6.5 Performance index when tuning the PID

The developed performance index should also benefit the tuning of the engine controls. It would be beneficial in tuning if the index indicates the reason behind bad control performance. The idle index value, oscillation detection and combined index value all indicate the reason for poor performance, and thus can easily be used as an aid in tuning.

The positive idle index indicates that the control parameters are tuned sluggishly. By increasing the proportional and integral gains the performance can be improved. However, before trusting the idle index value, the other values should also be inspected.

The oscillation detection value indicates a reason behind bad performance. If oscillation is detected, it may result from too high integral gain. By decreasing the integral gain value, the oscillation should be handled. However, this does not ensure that the control performance improves, as oscillation can also result from an oscillating system disturbance. It should be considered whether these two situations could be distinguished, and the reason could be indicated even more clearly.

The combined step response index also aims to indicate the reason behind bad control performance. The different performance classes, high performance, poor performance and sluggish performance all indicate different type of control performance. The poor performance value indicates, that the controller is tuned too aggressively, as the overshoot value exceeds ten percent of the reference value. In turn, the sluggish control result indicates that the controller is tuned too conservatively. Thus, based on the combined index value, the control parameters can either be increased or decreased.

The indices can also indicate if the tuning is going into the right direction. The values can be used as an aid to see if the modifications made to the control parameters are bettering the control result. By tuning the engine controls based on the performance assessment indices, it is easier to reach a uniform control result, and not have the control performance be too dependent on the person doing the tuning.

7. FUTURE DEVELOPMENT

This thesis forms a good basis on which the engine control performance index calculation can be developed. It is clear, that the implemented methods are not yet the most efficient and easy to understand. However, they do indicate which kind of performance assessment methods are most suitable for engine performance assessment. Furthermore, the results of this thesis can assist deciding on other methods to be implemented.

The developed algorithm can be optimized and streamlined further. Now, the calculation was implemented with the functionality as the main objective. However, the calculations could surely be made more efficient. This way the CPU power used could be minimized. The delay estimation algorithm implemented was very simple. In future, it needs to be improved to assess the control performance better. In addition, the assessment could be strengthened by utilizing more stochastic measures, such as the minimum variance based assessment. This way, the steady-state performance assessment would be more thorough.

The chosen methods were developed to mainly assess the performance when the reference change was stepwise. However, as could be seen from the engine tests, this was not the case at least for the gas pressure control application. The different control applications, and their dynamics should be inspected, to be able to determine what kind of changes are the most common. A method to assess a ramp and other continuous set-point change should be developed.

The current performance assessment methods provide multiple values. However, it might not be efficient to inspect and interpret all. Combining the index values might be an option. For the ease of interpretation, there could be a single value that indicates the performance during a set-point change and steady state conditions. The values that provide the most information during those times could be used to from a single value, from which the performance could be indicated from. If desired, the user could also see all of the values for further performance assessment, and to find the reason for bad performance. The combined index value could be a weighted sum of the different index values, thus giving more weight on the value that provides the most information during the present system state.

In the future, it should also be considered if the rise time, settling time and overshoot should have benchmark values. This could be determined by an expert, who knows how the controls should work. This way, they could be utilized to clearly indicate whether or not the step response is close to optimal or desired conditions. The values for unacceptable performance could be given, and if the performance exceeds those it could be indicated.

It should also be decided whether the calculation is added next to all the PID controllers in the individual applications, or if it should be included as its own application. If the algorithm becomes large and complex it might be beneficial to have it as its own application. However, based on the tests here, the performance configuration parameters may need to be controller specific. This would favour the performance assessment to be added in the individual applications next to the PID controls.

The tests performed did not include the adaptive or feed-forward controllers. These should also be tested and the algorithms updated accordingly. The benefit from adaptive and feed-forward controllers could be easily measured by comparing their performance assessment results to the ones for the basic PID control.

The future usefulness of the index could also be improved, by adding an indication on how much the performance was increased when parameters have been changed. This way, for example when tuning the parameters, it would be clearly quantified how much the performance has improved. This could be done by saving the performance assessment values from earlier tests in the calculation, then modifying the parameters, and assessing the performance again. The tool would be able to compare the values and indicate the improvement.

The future goal is to measure the control performance continuously. Every control loop should be considered individually, but a general assessment of the whole engine control performance should also be provided. In addition, an indicator on the most poor performing control loop should be included. This way, the most critical loops could be improved first.

8. CONCLUSIONS

Having a performance index evaluating the control performance has many benefits. When functioning correctly, it enables the performance to be assessed quickly and reliably. Furthermore, it makes the tuning of the controllers quicker and more straightforward. It also helps to detect poorly functioning control loops during engine operation, and makes it easy to react to control performance decreases due to changing process conditions. By ensuring that the process controls are functioning optimally, the efficiency of the whole process can be improved.

However, before the index can provide all these benefits, it needs to be developed and tested such that it works well in detecting control performance during different system states. First, it needs to be decided which kind of indices are most beneficial, and how they can be used in the specific instance. The implementation needs to take into account the different requirements of the system that it is being integrated in.

The research in this thesis provides a good overview of the methods available. Furthermore, the theory behind the methods considered to be used for engine control performance assessment is explained in more detail. However, the selection could have been made in many ways, and the suitability of the indices can really be seen only after they have been implemented and tested in the final environment.

The performance assessment methods implemented in this thesis provide an assessment of the control performance in different system states. They can also be easily implemented next to different closed-loop PID controllers, which makes the performance assessment of the various engine control loops possible. This is an important benefit of the developed methods. They do not need to be changed and re-implemented individually for each controller, which saves time and makes the assessment more uniform.

According to the tests made, the performance assessment algorithms provide a lot of information. However, the interpretation of the information is still not straightforward. In the beginning the aim was to create a single index value, but as it soon became evident that this was not sufficient, many values were calculated. This makes the performance assessment more complex, as the individual indices may provide conflicting results.

The interpretation of the indices was made easier by implementing the combined step response index. It decreased the index values from eight to six, and if the rise time, settling time and estimated delay are not taken into account, the final number on interpretable values is three. This seems more manageable, and decreases the time used to inspect the index values. The idle index will indicate whether or not the control result is sluggish, during an abrupt load disturbance or a reference change. The oscillation detection value indicates if there is an oscillation in the system. Finally, the combined step-response index value shows whether or not the control result is high performing, sluggish or poor for a stepwise set-point change.

Based on the research and implementation in this thesis, it can be said that there clearly exists many methods for assessing control performance. It can also be said, that even the simplest ones do provide a lot of value. However, it is better to implement a few indices well, and ensure that they work to bring the most value, rather than having multiple values. Testing is also an important part of the development process. It indicates the defects and shortages of the indices, and ensures that the developed methods are suitable for their purpose.

The most important realization from the testing part of this thesis was that it is very valuable to be able to test the functionality in its real environment. Only then, it is possible to really see how the process dynamics effect the performance index calculations, and how the individual process values behave during different system states. It was also noticed from the testing, that the same settings cannot be used for the different process control performance assessments. The configuration values, and possibly even the algorithms might need to be modified based on the process to gain the most benefit from the performance assessment. Based on the results of this thesis, three main problems that need to be solved in order to develop a functioning performance assessment tool are the performance assessment of the non-stepwise set-point changes, correct delay estimation, and assessing the performance of possible non-minimum phase responses.

The next step for the performance index development is to test the index functionalities in different engine control applications, and improve the algorithms based on the results. The implementation done here is only a base on which the performance assessment tool can be developed on, and it clearly has some shortcomings. However, the methods chosen do provide a good overview on the state of control performance in the engine. They will provide useful information once fully tested and modified to suit the purpose. The final engine performance assessment tool should be able to easily evaluate the control performance, and suggest ways to reach optimal levels.

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