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2025 | 171

Wärtsilä active NOx control development for lean burn engine

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

The local emissions and related regulatory frames have always been playing a strong role in the engine development. Both global and local emissions compliance are key to enabling sustainable power production. In the last years, Wärtsilä has put a lot of R&D effort in developing robust gas engine control to secure engine optimal operation throughout its lifecycle and independently from external factor variation such as ambient conditions.

Air-fuel ratio control plays a fundamental role in achieving NOx compliance, securing thermal efficiency while guarantying safe and reliable operation of natural gas engines. The introduction of latest two-stage turbocharging has highlighted further the criticality of charge-air pressure control and its sensitivity to various factors such as ambient conditions and fuel characteristics.

Engine performance monitoring combined with modern automation and after treatments technologies have created together the need and the opportunities to develop and introduce an adaptive control application that yields benefits to all Wärtsilä gas engine customer operation.

While controlling the charge air pressure level remains the base for air-fuel ratio control, cylinder pressure digital system processing embedded in the engine control system offer possibility to extract combustion heat release that can be correlated to NOx formation. The combustion heat release is supplemented with NOx sensor provide the input for a very effective and robust charge-air control algorithm. The development, validation and field introduction of Wärtsilä state-of-the-art active NOx control will be further described in this publication.

1 INTRODUCTION

Enabling energy production worldwide has been a key focus for Wärtsilä for decades. From the mid 90s Wärtsilä has been developing both Diesel and Lean Burn natural gas engine generator sets optimized for land base power production.

The entire generating set portfolio has been developed with purpose to offer energy producers best possible assets to generate electricity safely, cost-effectively and in a sustainable manner.

Today the state-of-the-art generator set, as shown in figure #1, can be delivered as equipment or as part of a complete turn-key power plant to be installed and operated in any region of the globe with the guaranty of compliance to local environmental regulations.

Figure 1. Wärtsilä W31SG Genset

Emission compliance is a key requirement when delivering an engine power plant.

Typically, emissions of carbon monoxide, (CO), hydrocarbons (THC) and particulates matters (PM) are restricted. Particularly, nitrogen oxides NOx (NO, NO2) gases emissions are strictly regulated.

NOx gases contribute to formation of smog, acid rain and impact atmospheric ozone.

NOx regulations are local and there are many different national or regional limits in place. In some areas NOx release to atmosphere is prohibited and engine must be supplemented with selective catalyst reduction (SCR) exhaust gases aftertreatment systems.

NOx formation is resulting from chemical reaction between oxygen and nitrogen during combustion process, taking place at high temperatures.

Natural gas lean burn Otto combustion chemical reaction takes place at lower temperature than diesel combustion and therefore a natural gas engine produces substantially less NOx than a diesel engine for comparable power output and thermal efficiency. This makes lean burn gas engines an attractive solution for power generation in places where natural gas is available, and NOx emissions are stringent. NOx emission level is a key requirement of lean burn gas engine combustion performance optimization.

The lean burn combustion process relies on a precise and robust air/fuel ratio control. Air/fuel ratio control is fundamental to guaranty engine integrity, fuel efficiency and emission compliance.

This Air fuel ratio engine control application has been an essential part of the engine performance automation and control development and important part of engine calibration.

Various factors may impact air fuel ratio control accuracy and precision. While engine calibration is essential for NOx emission, external factor such as fuel quality or ambient conditions, can potentially lead to intermittent NOx emission deviation or fluctuation.

The NOx deviation puts emission compliance at risk and also may result in increased fuel cost, and/or increased urea consumption in the aftertreatment systems.

Progress in digitalization, control and sensor technologies has brought new opportunities for improving air fuel control method.

The cylinder pressure sensors and digital signal processor (DSP), that once were laboratory instruments only, are now available on all Wärtsilä gas engines as integral part of control systems. The cylinder pressure based control applications can be further developed to bring additional benefits.

Initially introduced for cylinder load balancing, firing pressure monitoring and knock avoidance the cylinder pressure system can also be used for precise combustion monitoring and control.

Combustion heat release derived from cylinder pressure curves is fundamental in describing engine combustion process performance. The combustion heat release provides insight about the timing and the speed at which fuel is burning during the combustion process.

A strong correlation can therefore be established between the combustion heat release characteristic and combustion temperature, eventually translating into NOx emission formation.

Additionally, automotive type “Smart NOx” sensor technology has made its way from automotive to power generation industry: The sensors are commonly used in SCR aftertreatment operation and, also as control input, for the urea dosing system before catalyst.

The sensor signal provides oxygen and NOx concentration values. Naturally it can also be used to enhance engine air fuel ratio control of power plant engines just as it is used for this function in automotive industry.

Wärtsilä has developed an “Active NOx control” utilizing above mentioned state-of-the-art technologies bringing operational and performance benefits both for Wärtsilä and its power plant customers. The development of active NOx control will be motivated and described in this article.

2 LEAN BURN GAS ENGINE CONTROL

The control system has become an essential part of the engine management. The control must guaranty safe and robust operation. Fundamental function of the control system is the machinery protection. Machinery protection prevents overspeed, overload and preserve engine mechanical integrity.

Beside machinery protection and among the many control functionalities, the combustion control is most relevant to NOx compliance and essential to guaranty engine is operated according to expected performance. Engine performance is measured in power output (BMEP), thermal efficiency (%) and NOx Emission (g/kWh).

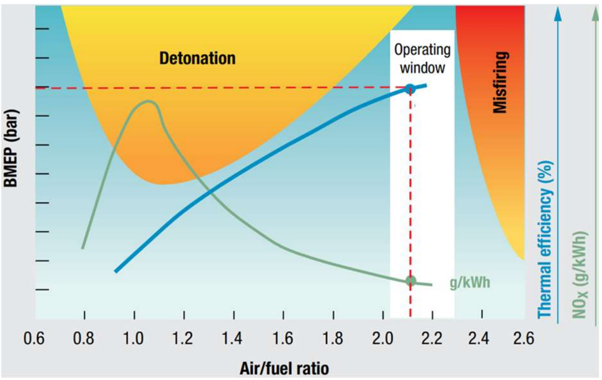

Figure 2. Lean burn gas engine operating window

The lean burn gas engine process relies on very precise air fuel equivalent ratio control. At high output, the operating window, as it is shown in figure 2, is narrow. Air/fuel ratio must remain away from detonation (Rich limit) and misfire (Lean limit).

The combustion control of a lean burn gas engine relies on 3 fundamental control processes: Fuel injection, is setting the amount of fuel needed. Ignition is defining the start of combustion. Finally charge air pressure control is providing the air.

2.1 Fuel injection process

The fuel gas is injected during engine intake stroke. Injection is achieved by opening main gas valves MGV’s. MGV’s are installed between the gas manifold and the inlet channel of each cylinder. The gas manifold pressure is controlled higher than the air receiver. The MGV opening is synchronized with the inlet valves opening by adjusting injection timing in crank angle. The injection duration is the main fuel injection control parameter as it sets engine load. With a longer injection duration, more fuel is injected in the cylinder resulting in higher engine load. Fuel injection is a cyclic control process. Injection is represented in figure 3.

2.2 The ignition process

Ignition is critical for combustion control. Wärtsilä gas engines uses different ignition systems for dual-fuel (DF) ad spark gas (SG). A diesel micro-pilot injection in the main chamber will start the combustion of dual fuel (DF) engine type. In the spark gas (SG) engines, a spark plug ignites fuel in a pre-combustion chamber that will in turn ignite the main chamber. The main control parameter for this process is the crank angle timing of ignition at the end of the compression stroke initiating the combustions. The ignition system is designed for robust and repeatable ignition ensuring controlled and stable combustion cycle after cycle.

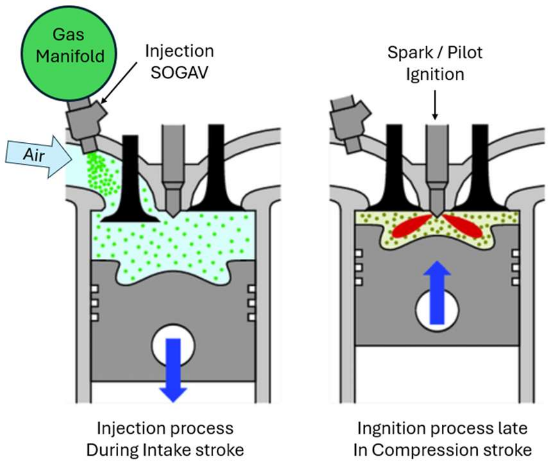

Figure 3. Injection and ignition process

2.3 Charge air pressure control process

Lean burn gas engine is always equipped with a turbocharger that uses exhaust gas expansion thru a turbine to power a charge air compressor. The compressor increases pressure in the air receiver increasing substantially air mass available for combustion. An exhaust waste gate (EWG) is used to regulate flow thru the turbine, providing a precise way to control the charge air receiver pressure.

The charge air pressure control using the EWG is the primary method ensuring combustion takes place at desired air fuel ratio with a direct impact on NOx emissions:

At a given engine load (equivalent to injected fuel gas quantity), EWG closing increases charge air pressure and air fuel equivalent ratio. The combustion is leaner, resulting in slower, cooler combustion yielding less NOx.

Alternatively opening EWG decreases charge air pressure and lowers air fuel equivalence ratio, resulting in an enriched, faster and hotter combustion that will produce more NOx.

Charge air pressure control is a closed loop process: The controller constantly measures charge air pressure feedback, compares it with a reference value and calculates a control value for the EWG actuator.

This charge air pressure reference value is recorded for each load in a reference map. Part of the calibration effort of the engine is defining this reference map, to satisfy engine performance and NOx compliance. Charge air pressure control is described in figure 4.

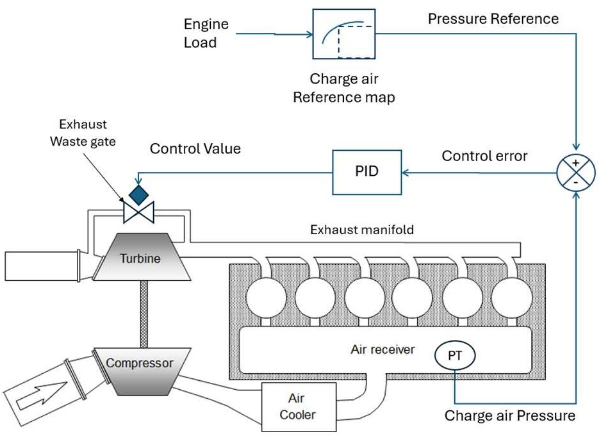

Figure 4. Charge air pressure control

3 ENGINE CONFIGURATION, CONTROL AND PEFORMANCE CALIBRATION

As described previously controlling charge air pressure reference map is the primary method for adjusting air amount available for combustion inside the cylinder. However, many factors impact the air mass available in cylinder for combustion at a given receiver pressure.

3.1 Specific engine configuration

First the charging air system is configured to satisfy the airflow requirement thru the engine. The EWG must have adequate control margin in all conditions to be able to regulate air fuel ratio over complete engine operation range

For example, oxygen content of ambient air depends on altitude, and in some cases, it is necessary to proceed with a turbo matching and adjust turbocharger components so the system can supply enough air flow (and oxygen) to the engine. This is also the case in extreme ambient temperature applications.

Once the charging air system is set, and sufficient waste gate control margin is guaranteed for the plant application, ambient condition must still be considered carefully.

3.2 Ambient compensation factor

Obviously, charge air receiver temperature, impacting density of charge and compression end temperature, is critical. For this reason, the temperature of charge air is controlled using a charge air cooler. Temperature is controlled to be constant and a deviation from the reference charge air temperature must be compensated by applying a charge air pressure offset to reference map. The ambient temperature has impact on charge air temperature control range. The variation in ambient air humidity must also be compensated for.

Those ambient compensation factors are part of the engine control parameter calibration effort when delivering an engine.

The engine standard configuration and parameters are set to cover the majority of power plant application. Sometimes a non-standard engine is delivered with a specific set of control parameter calibration values.

3.3 Engine derating and avoidance strategy

Engine derating consists of limiting the engine load when engine machinery protection or external factor, such as ambient conditions and/or gas fuel quality, do not allow safe and sustainable operation of the engine at full load.

Typical derating may be due to a temporary limitation in plant cooling capacity and impossibility to limit charge air temperature. In this case load will be reduced to avoid pre-ignition and uncontrolled combustion.

Fuel quality is also extremely critical and a common reason to derating engine load. Fuel gas composition impact auto ignition temperature of the air-fuel ratio as well as combustion speed. This can lead to knocking phenomenon and catastrophic failure of engine components. For reciprocating engines, the key indicator of fuel quality is expressed in methane number MN. The MN can be used to calculate the maximum sustainable load for an engine at nominal NOx.

Derating is very costly for a plant operator. First the engine thermal efficiency is decreasing substantially with load, resulting in electricity production cost increase.

When derating the operator cannot realize the full use of the generator he has purchased. Plant operator also often have contractual agreement to guaranty plant capacity and support electrical grid. Limiting, even temporarily, the plant capacity may be problematic for the consumer or grid operator.

For this reason, engine control has been developed to offset charge air reference map and operate engine at lower NOx level. This allows operator to avoid load derating, reaching full engine output while securing NOx compliance.

The derating avoidance using lower NOx may be set by calibration using a different charge air pressure reference map or may be triggered by external plant automation signal. Signal may be set by an operator or even automated using gas composition analyser providing the MN as input for engine control system.

3.4 The importance of NOx compliance and NOx control.

The engine performance including NOx compliance is always checked in a factory test run. Customers can witness a factory acceptance test (FAT) of their gensets, prior delivery, or request a product conformity test (PCT), during which, engine performance is recorded, and checked against, the performance guaranty contractual values.

In addition to product conformity testing at factory many projects require emission guaranty measurement at site. Emissions are typically measured at steady state load and stabilized conditions.

Some engine power plants are equipped with continuous emission monitoring systems (CEMS). The CEMS are required to maintain plant operation permit. The CEMS allow the plant to report steady state load operation emission in averaging period, typically 15,30 or 60min. All dynamic load emission variation must also satisfy permit limits. The emission legislation may also be stated as daily or yearly average.

For installation without CEMS the emission measurement is performed at time of engine commissioning, demonstrating engine compliance before plant operational hand over. Following commissioning emissions measurement are carried out annually or bi-annually by authorities or financial institute such as international finance corporation (IFC)

Requirements by authorities on measurement may differ a lot between areas and can cause challenges for our customers.

Beyond the obvious legal risk to see operation permit suspended there is substantial operational cost if engines are not operated at nominal NOx. The thermal efficiency of gas engine increases with NOx. Overcompliance (operating below NOx limit) will result in increased fuel consumption. Alternatively operating above the NOx target may also result in operational cost increase. High NOx operation fuel consumption may decrease but thermal load will increase and may have impact component lifetime. In addition, for plant equipped with SCR, operating above the NOx limit comes with increase in urea consumption.

The relation between NOx and fuel consumption is illustrated in figure 5, using the example of a standard W31SG engine operating at full load. The gain in fuel saving when exceeding NOx is not as much as the fuel penalty when running lower NOx at equal deviation.

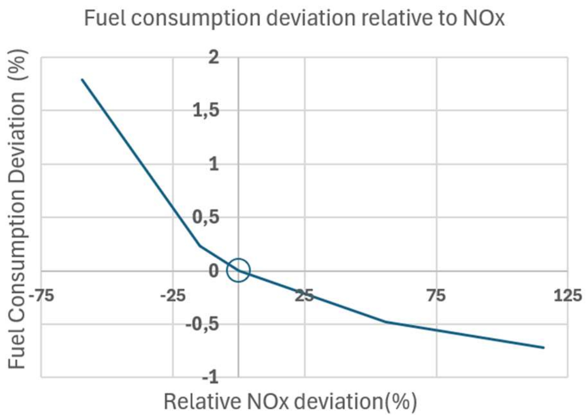

Figure 5. NOx impact on fuel consumption

All in all, the operator shall strive to operate as close as possible to the optimum at all times. To do so, it might be necessary to adjust the engine parameter at site occasionally and proceed with some recalibration of the charge air reference map and/or compensation factors.

This is the case at plant commissioning, but this type of engine performance tuning is also done periodically throughout the engine lifecycle.

Wärtsilä may also propose some seasonal optimization for some customers operating in areas with extreme ambient conditions.

The increased complexity of engine performance parameter calibration and the need for site-specific optimization has led Wärtsilä to develop a new active NOx control application enhancing the air fuel ratio control with state-of-the-art cylinder pressure processing and direct NOx sensor technologies. The objectives of active NOx control development are:

- Reduced engine calibration work in factory
- Reduced performance tuning work at site
- Improved NOx control precision and accuracy
- Optimized operational cost for plant operator
- Automatic derating avoidance
- Robust and failsafe control application

4 NEW COMBUSTION HEAT RELEASE BASED AIR FUEL RATIO CONTROL

All Wärtsilä Gas engines have been equipped with cylinder pressure sensors since year 2010. Investing in the technology has brought many benefits on engine products for Wärtsilä customers. The sensor technology has become robust: Sensors, such as the one shown on figure 6, are rated up to 350Bar. Throughout the years Wärtsilä did collaborate with few suppliers to mature and validate sensor technology against thousands of running hours in harsh engine conditions. The pressure sensors precision and accuracy are enabling many control applications.

Figure 6. Cylinder pressure sensor

Cylinder pressure control applications potential is broad and has been well described in literature. Wärtsilä has already published on the topic. [1]

The sensors connected to the control system have been instrumental in the continuous improvement of gas engines performance. Cylinder pressure technology is now mature and well established as engine control input. A fair amount of application is already implemented on Wärtsilä gas engines:

- Pilot optimization (Dual Fuel Engines)
- Detection of high peak pressure
- Cylinder load balancing
- Knock and pre-ignition detection
- Weak- and misfire detection
- Fuel flexible engine control

4.1 Combustion heat release measurement

Air/fuel ratio is the latest cylinder pressure control application developed as part of active NOx control. Because of already existing sensors and control system processor capacity it was possible to implement air/fuel ratio by software coding only.

The air/fuel ratio application is based on combustion heat release control. Combustion heat release is calculated from cylinder pressure traces. The measured cylinder firing pressure is compared to a thermodynamic model of the compression pressure providing heat release and cumulative heat release curve. Figure 7 shows a measured cylinder firing pressure trace and calculated cumulative heat release curve example.

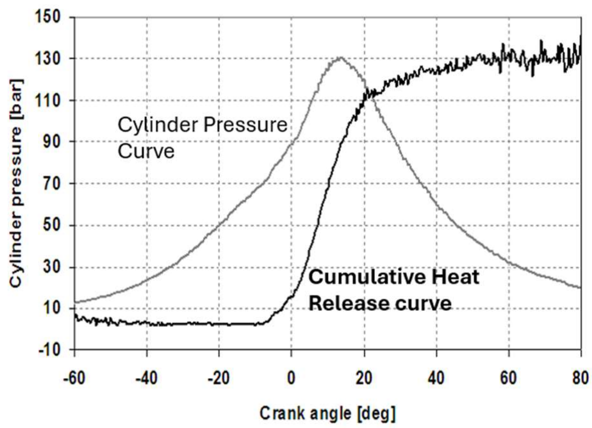

Figure 7. Pressure and cumulative heat release

Key combustion characteristics, such as combustion phasing versus engine timing and combustion duration, are extracted and can be used as control feedback, to optimize the air/fuel ratio control.

There is a strong correlation between heat release and combustion temperature and for this reason controlling heat release is equivalent to controlling NOx formation: Combustion cycle displaying equal heat release characteristic will produce the same amount of NOx. That is fundamental for new active NOx control application development.

4.2 Combustion heat release control process description

For the control implementation, the measured combustion heat release will be compared to an optimum reference and the difference will be used to offset the charge air pressure as described in following figure 8.

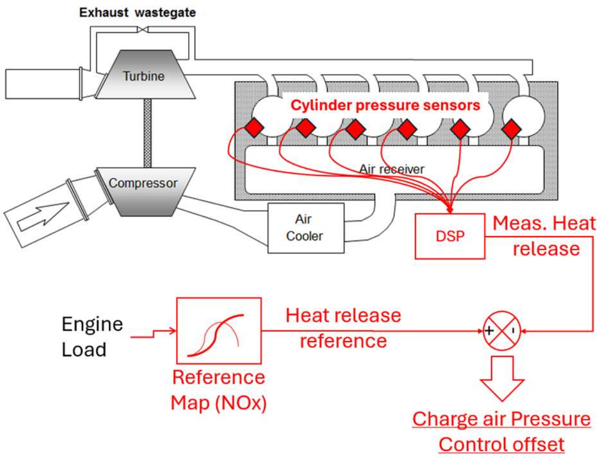

Figure 8. Combustion heat release control

This way combustion heat release is not replacing charge air pressure control, but the method will be combined. Both methods are used in a complementary way to achieve a robust and more accurate air-fuel ratio or NOx control.

In fact, monitoring and limiting the charge air pressure offset will indicate a problem with cylinder pressure sensors and can trigger an alarm on the control system.

5 USING SMART NOX SENSOR AS DIRECT NOX CONTROL FEEDBACK

Smart NOx sensor technology rise has taken place in the automotive industry. These sensors have become unavoidable inputs for cars and trucks engine management and exhaust after treatment systems: The sensors fast sampling of NOx and O2 concentrations enable precise air/fuel ratio control and make for optimized anti-pollution systems control strategy. Figure 9 shows a sensor and its processing unit.

Technical description of smart NOx sensor technology is widely available. An excellent summary can be found on DieselNet in article entitled “NOx Sensor” with following abstract: “*Automotive NOx sensors are primarily of the amperometric type, with two or three electrochemical cells in adjacent chambers. The first cell electrochemically pumps O2 out of the sample, so it does not interfere with the NOx measurement in the second cell. Commercial sensors, available from several suppliers, are used for the control of NOx adsorber and SCR aftertreatment. NH3 sensors have been also developed for use in SCR systems.”* [2]

Figure 9. An automotive smart Nox sensor

Wärtsilä has also been interested in this sensor technology for number of years. Automotive mass production has driven cost of such sensor down to only a fraction of what complex and bulky exhaust gas analyser instruments costs. The sensors benchmark was initiated in engine laboratories over 15 years ago. Laboratory is the ideal place for such technology benchmark, where engines exhaust gas streams are constantly monitored using calibrated exhaust gases analyzers. In such environment it was possible to systematically assess smart NOx sensor precision, accuracy and robustness. In addition, it was very important to understand if the technology, developed for automotive, was suitable for power generation engines. Indeed, when considering sensor applications, the expected duty, endurance and exhaust gas composition characteristics are different from automotive industry. As an example, a baseload power production engine assumes up to 8000 running hours of operation per year, a different order of magnitude when comparing the expected duty of sensor in automotive application. There are also major differences between exhaust gas composition and conditions when comparing for example lean burn gas engine: Lower nominal NOx level and temperature that do not exceed 400°C after turbine on a lean burn gas engine.

5.1 Smart NOx sensor integration

Sensor integration is specific to power plant environment. In most automotive applications the exhaust duct diameter is well under 100mm section. The NOx sensor can be installed flush to the few mm thick wall of the duct, so the sensor cell is exposed to the exhaust gases stream.

In the power generation world, engine can output 10MW and the turbocharger exhaust duct, reaching over 600mm diameter, are build of nearly 10mm thick material. Special flow-thru sampling probes are needed to mount the sensor near exhaust duct and provide it is consistently exposed to exhaust flow. The sampling arrangement principle is described on following figure 10.

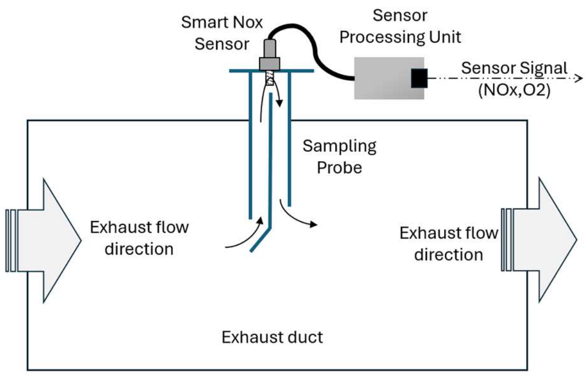

Figure 10. Smart NOx sensor probe for large duct

Regarding connectivity the sensor processing unit must be supplied with electrical power at 12V/24V and an enable logic signal input that manages integrated sensor electrical heating element. The sensor output is an automotive CAN protocol signal containing sensor diagnostic in addition to NOx and O2 values.

The sensor can be connected directly to Wärtsilä UNIC control system COM module or alternatively to plant automation PLC (Programable Logic Controller).

5.2 NOx sensor control process

The NOx and O2 concentrations, measured in exhaust gas stream, are used as control feedback signal for active NOx control application. High level control process is described in following figure 11.

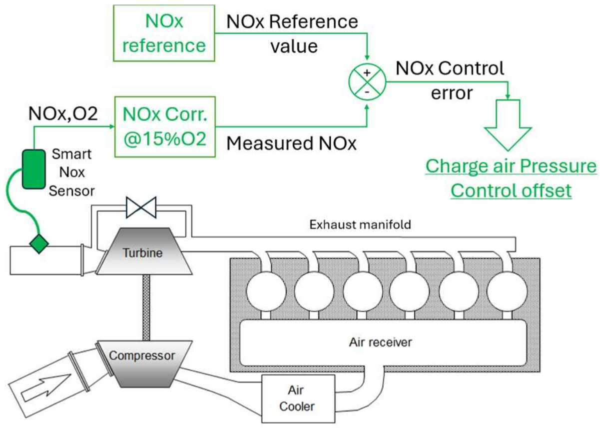

Figure 11. NOx sensor used as process input

The NOx concentration is always corrected with oxygen so it can be compared to requirement from the standard measurement method. For example, “TA Luft” NOx level is stated at 90ppm NOx at 15% O2 Dry. For this reason, the O2 concentration from the sensor is used to correct measured NOx concentration.

The corrected NOx measurement value is compared to the engine nominal NOx reference and the NOx control error is translated into a charge air pressure offset. The charge air offset, based on direct NOx measurement, will be used in the active NOx control where it is combined with charge air control application.

One critical aspect of using NOx sensor as control input for active NOx control is that application must be failsafe and cope with potential sensor failure.

5.3 Active NOx control implementation

The active NOx control development is a significant upgrade of control methodology for Wärtsilä gas engines.

The charge air reference control method remains active in the background, but it is supplemented by two additional control loops. First the combustion heat release control process directly adjusts combustion temperature and NOx formation. It is less sensitive to calibration imperfections and local remote site conditions than the charge air pressure method. In addition, direct NOx measurement using a sensor is used to remove a potential NOx deviation from expected nominal.

The implementation is done by software update of the air/fuel ratio control application. While additional parameters and new control logic were needed, a large part of the effort was focused on the smart NOx sensor and engine mechanical and electrical integration. Special attention was paid to the robustness of the active NOx control.

First the combustion heat release may be disabled in case of multiple cylinder pressure sensor failure. This would also be the case if combustion heat release offset would indicate a large deviation from the charge air reference map. As the base charge air reference control is active in the background, it provides a plausibility check for combustion heat release method.

The NOx sensor control is also failsafe. Different sensor failure modes have been considered. In the event of a sensor internal failure, the NOx sensor diagnostic signal is used to disable the relevant charge air offset effectively. This is also the case in the event of a CAN communication issue between the engine and the control system.

One of the main concerns related to taking NOx sensor into use as control input is the deactivation overtime of the sensor electromechanical cells. The deactivation is expected and even compensated for in sensor processing unit. Such deactivation will result in possible NOx concentration measurement being under the actual exhaust NOx concentration. In order to mitigate the NOx sensor deactivation, the relevant charge air offset is limited in range. Again, the charging air reference map provides a plausibility check. In addition, it is recommended to replace the NOx sensor as part of generator sets scheduled maintenance. The cost of a sensor replacement is compensated by the expected operational cost benefit of running active NOx control application. Again, operation at optimum NOx saves both fuel and urea for SCR. The active NOx control process is described figure 12.

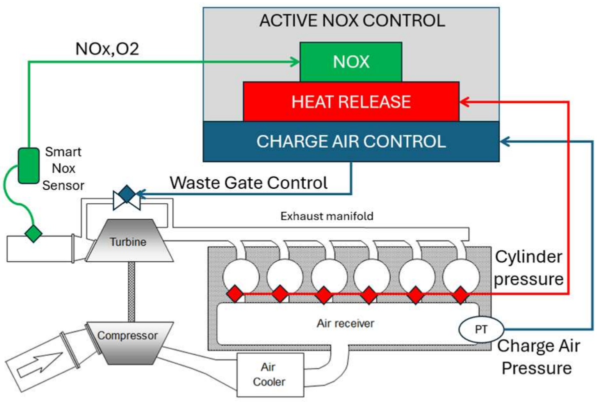

Figure 12. Active NOx control process

6 LABORATORY VALIDATION AND FIELD INTRODUCTION

The active NOx control was developed in a dedicated project. Project objective was to development, test and validate the new control, in laboratory and selected field installation, to support industrialization.

For this reason, all the expertise were involved in the development during the project. A large part of the development was specified by engine performance expert and implemented with automation and control experts.

One of the main efforts in parallel to the functionality and software development was the integration and validation of the Smart sensor installed on exhaust gas engine module directly downstream the turbocharger turbine outlet.

7 LABORATORY ENGINE TESTING

Wärtsilä 20V31SG laboratory engine was used to test and validate the prototype software application. Test team. performance and control experts did run the engine and adjust application parameters in all static and dynamic load conditions.

7.1 Software testing and parameter tuning

A big part of the development is to define the correct processing of cylinder pressure heat release and NOx in term of averaging, filtering. The control input signal conditioning must be consistent with expected performance of the control algorithm.

Once the control inputs are ready it is necessary to adjust the control value dynamic is compatible with charge air pressure control process. The focus was especially on defining the rate of change of the NOx and combustion heat release charge air offsets, to improve steady state air fuel ratio control.

The software parameters are adjusted one by one, and tested against different engine dynamic operation, to secure control loops are not fighting each other and do not create instability. The following figure 13 is showing charge air heat release duration and NOx dynamic response when lowering charge air reference -100mBar.

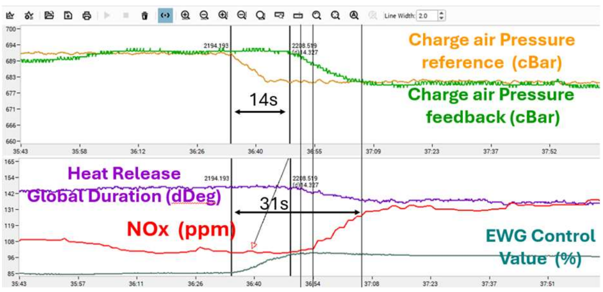

Figure 13. Response to CAP reference change

In addition to the performance and functionality parametrization all failsafe situations are demonstrated. For example, NOx sensor failure is artificially triggered to check the active NOx control does react as anticipated.

Following software development iterations, the application is left to operate the laboratory engine and prove the new active NOx control is mature.

Finally, the prototype application can be released as a standard software version and rolled out on production engine.

7.2 NOx sensor integration benchmark

Part of the laboratory engine test time was used to define requirement for the smart NOx sensor installation. Multiple sensor supplier and probe setup were fitted to exhaust duct on laboratory engine. The setup is shown on figure 14. The 3 sensors are installed on different exhaust probe and one of the probes has a flushing device. The flushing may be needed in some installation to avoid sensor fouling. Other sensors were also placed further downstream the exhaust duct.

Off course a single sensor is used as active NOx control input for the engine at a given time.

All sensors were monitored 24/7 and values compared to calibrated exhaust gases emissions analyzers. Different connectivity options were also tested, direct CAN connection to engine control system as well as external plant PLC.

This connectivity options are needed for plant retrofit and plant with SCR. This test was very valuable to document and develop instructions for field introduction. For example, it was possible to define physical placement and orientation of the probe.

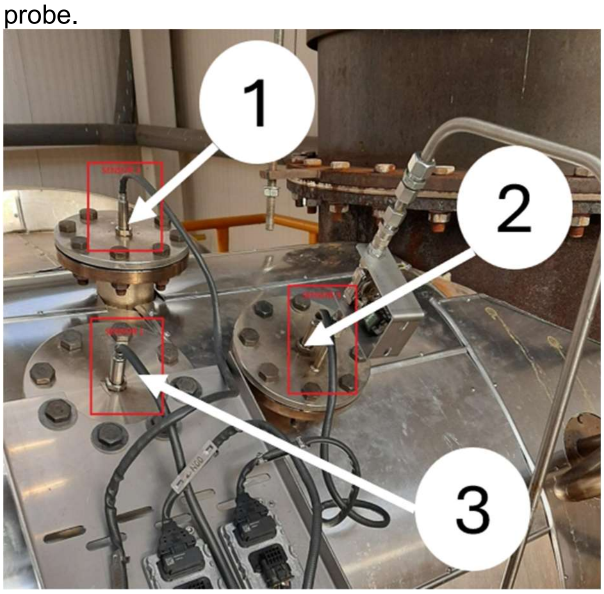

Figure 14. Smart NOx Sensor integration lab setup

7.3 Field engine testing

The active NOx control was released and implemented on a field installation. Two neighbour W20V31SG gensets were operated in parallel for a period of time to assess the benefit of the active NOx control application. Active NOx control was disabled on engine A and enabled on engine B. In the following figure 15, engine A NOx concentration as a function of charge air temperature. Each dot represents a 5min averaged NOx concentration.

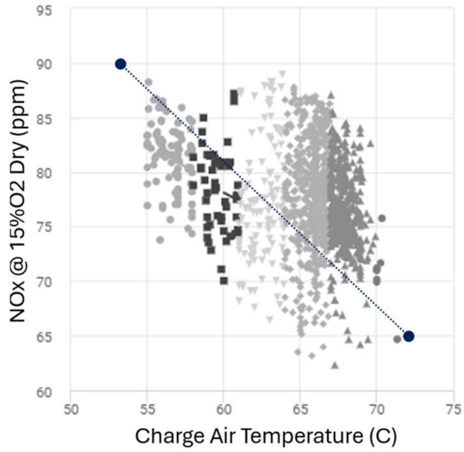

Figure 15. Engine A, Active NOx control disabled

The NOx Target is lower according to temperature to avoid derating of the engines when ambient temperature increase (Impacting charge air temperature). In this case NOx can deviate more than 10ppm from the target. Especially for higher temperature. Below figure 16 shows the same graph for engine B operating with active NOx control enabled.

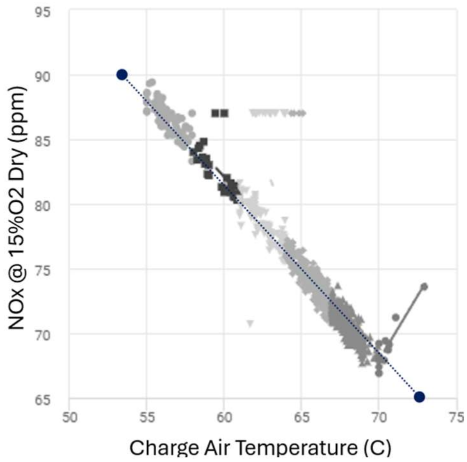

Figure 16. Engine B, active NOx control enabled

The NOx deviation from reference is well under 5ppm in all temperature conditions when enabling new Active NOx control functionality.

8 CONCLUSIONS

Emission compliance is a critical part of power generation. NOx emission reference is essential to operate engine at the optimum performance.

Some improvement in NOx control can be achieved using new technologies such as NOx sensor and capitalizing on the cylinder pressure sensor already used for other applications.

Active NOx control has been developed and is available on all Wärtsilä power generation gas engine portfolio. The active NOx control is bringing flexibility and improvement to our customer in regard to NOx compliance throughout the complete lifecycle of the engines.

Active NOx control is keeping engine running at an optimum independently of ambient conditions and fuel quality. Operational cost benefit saving fuel and urea also contributes to lowering CO2 emissions. The benefit of the new control has been demonstrated in laboratory and field installations.

The control upgrade also brings operational benefit as the performance parameter calibration effort is reduced. The application is also more suitable for derating avoidance.

9 DEFINITIONS, ACRONYMS, ABBREVIATIONS

NOx (Nitrogen Oxides) is used to qualify Nitric Oxide (NO) and Nitrogen dioxide (NO2) gases.

W31SG Wärtsilä engine product name 31cm Bore Spark ignited natural gas ga engine.

CO2 Carbone dioxide, CO carbon monoxide.

THC Total Hydrocarbon Emission

PM Particulate Matter

O2 Oxygen gas

SCR Selective Catalytic Reduction is an aftertreatment system used to convert NOx into Nitrogen gas and water

DSP Digital System processor

BMEP Break Mean effective Pressure

MGV Main Gas Valve

SG Spark Gas ignition engine

DF Dual Fuel engine

EWG Exhaust Waste Gate

PID Proportional Integral Derivative controller

PT Pressure transducer

MN Methane Number

FAT factory Acceptance Test

PCT Product Conformity Test

CEMS Continuous Emission Monitoring Systems

IFC International Finance Corporation

NH3 Ammonia

CAN Controller Area Network

PLC Programmable Logic Controller

UNIC Wärtsilä Engine Control System

COM UNIC Communication Module

TA Luft Technische Anleitung German pollution control regulation reference for gas engines

CAP Charge Air Pressure

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