

SOLUTIONS FOR LOCAL ISOLATED GRID WITH HYBRID SYSTEM INCLUDING WIND TURBINE INTERCONNECTION

Nguyen Duc Huy¹, Tran Nam Trung², Tran Khanh Viet Dung³
Nguyen Phung Quang¹, Vo Hong Thai⁴

¹ Hanoi University of Science and Technology

² Vietnam Electricity

³ Vietnam Oil and Gas Group

⁴ Vietnam Petroleum Institute

Summary

The interconnection of distributed energy systems (renewable energies, diesel generators, and hybrid systems etc.) with utility grid has been one of the most important R&D orientations for many years. The majority of the utilities in the world were not conceived to accommodate large-scale distributed energy systems which can cause problems to the utility grid and different solutions have been developed and proposed. However, the hybrid system (wind turbines and diesel generators) with large capacity of wind turbine interconnection to the local isolated electrical grid on an island has not yet gained a comprehensive solution. In this paper, we present the solution for our hybrid system in Phu Quy island - Vietnam, which has 3 wind turbines (3 x 2MW) and 6 diesel units (6 x 0.5MW) interconnected to the local isolated grid (22kV). Our goals are to maximise the penetration of wind power and keep the system stable. Analytical and simulation studies were performed in order to validate the accuracy of the proposed solution. The results were approved by Vietnam Electricity and the solution proposed is currently being used for the stable operation of our hybrid system.

1. Introduction

Phu Quy is the largest island of Cu Lao Thu, in Binh Thuan province, Vietnam. The island's area is approximately 16.52km² with 24,000 residents. The main generation source for the island up until 2012 was 6 diesel generators with total capacity of 3MW, commissioned in March 2009. This source of energy met the basic residential demand and part of industrial usage on the island. The downsides of using diesel generation were high cost (~ 24US cents/kWh) and high carbon emissions [1]. This imposed a restriction on economic and social development, trading and commercial services on the island. The current load on the island is primarily residential (~ 2MW). Phu Quy island is in the region of the highest wind potential in Vietnam - average wind speed over a year is around 9m/s at 60m hub height. This is an ideal speed for developing wind power. The wind power project in Phu Quy island with the total capacity of 6MW was commenced in 2010 and commissioned in January 2013.

The wind-diesel hybrid system in Phu Quy island currently consists of 6 diesel units with capacity 6 x 0.5MW and 3 wind turbines 3 x 2MW (Vestas V80). While operating this hybrid system, there existed a number of techni-

cal challenges that needed resolving including designing an operation scheme for the hybrid system and developing a suitable SCADA system for operational purposes. In addition, research has been undertaken to improve the penetration of wind power in order to reduce the electricity tariff and the amount of carbon released from burning fossil fuel on the island.

Actually, there are a number of applications in the world that currently deploy the wind-diesel hybrid configuration such as the isolated grid in Alaska-US [2], those in remote areas in Australia and larger scale applications in the Canary islands, Spain [3]. The technical constraints for each particular network depend on several factors: wind turbine technology, ratio of installed wind capacity over diesel generation and load characteristics (controllability and reliability required). Therefore, there is no universal solution for wind-diesel hybrid systems; an optimal operation scheme needs to be developed for each case.

The power system in Phu Quy island belongs to the high penetration class according to NREL's classification [2]. During the development and operation of the system, there existed a number of technical challenges that needed

resolving. This paper presents results found from a study to improve Phu Quy system's stability, reliability and penetration of wind power. The structure of this paper is as follows: Section II introduces technical constraints for the hybrid system in Phu Quy island, Section III gives an overview and analysis of solutions for enhancing the wind power penetration. Section IV presents a financial analysis for investing in a low-load diesel generator. Finally, conclusion and recommendations are provided in Section V.

2. Current operation scheme and technical constraints

2.1. Constraints on frequency stability

In a 3-phase power system with synchronous machines, keeping the system frequency within acceptable tolerances is equivalent to maintaining a good balance between generation power and demand. In such a system the synchronous generator speed is always kept at the synchronous speed. The rotor inertia, turbine inertia and speed governor play an important role in stabilising and keeping the system frequency at 50/60Hz.

The principle of grid connected synchronous machines does not apply to wind turbine generators. Wind turbines nowadays utilise a doubly-fed induction generator (DFIG) or permanent magnet synchronous generator connected to grid via a bi-directional power electronic converter. The rotor speed can be varied within a

wider range in order to harvest maximum wind energy. For these two technologies, the rotor inertia does not play a role in stabilising the system frequency. Therefore, a common problem for a system with a high penetration level of wind power is reduced inertia [3]. When large switching events occur, the system frequency changes affecting equipment operation and may trigger frequency relays.

For the power system in Phu Quy island, due to the high ratio of wind power capacity over diesel generation capacity, the number of diesel generators operating simultaneously plays an important role in the system inertia. The phenomenon of reduced inertia can be clearly seen from a partial load shedding simulation in Fig.1.

On the other hand, simulations also show that with the same number of diesel units operating, increasing the power ratio of wind power has negligible impact on the system frequency response (Fig.2).

The existing Cummins diesel generators in Phu Quy island have reasonably good frequency response and controllability. In practice, with more than 3 diesel generators operating, the hybrid system is relatively stable.

According to technical references, Vestas V80 wind generators also have the capability of adjusting power generated to the system frequency thus helping improve the stability of system frequency. However, this function has not yet been activated.

2.2. Constraints on voltage stability

In addition to the requirement of balancing active power, a power system also requires a balanced reactive power. Balancing reactive power is directly related to the grid voltage. Cummins diesel generators in general have good reactive power generation capability with rated power factor in the range of 0.8 - 0.85.

The capability of generating reactive power of wind turbine generators in Phu Quy island is limited: the generator power factor falls in the range of 0.98 - 1. This means wind generators have little ability in controlling voltage at the connection point. The load in Phu Quy island is mainly residential with very high power factor (0.92 - 0.93). The load therefore consumes very little reactive power and operational experience shows insignificant technical problems relating to voltage stability. However, the limited capability of generating reactive power from wind turbines would become a challenge when increasing the

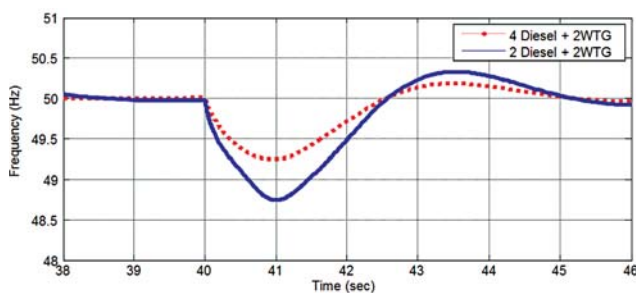


Fig.1. Frequency response to a load switching event with different number of diesel generators

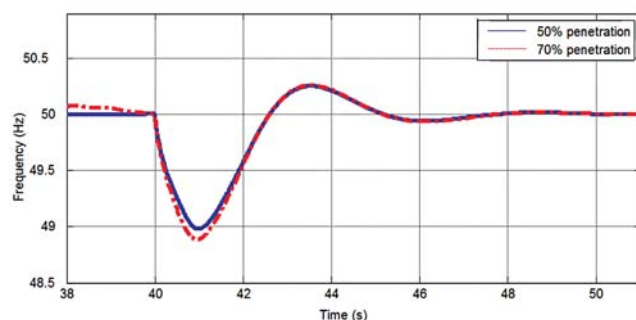


Fig.2. Frequency response to sudden load increase at different penetration levels

penetration level. When the penetration level increases, the number of diesel generators decreases leading to a drop in reactive power reserve. Besides, the use of diesel generators to meet reactive power demand results in those generators operating at a low power factor meaning low efficiency.

2.3. Constraints on diesel generator operating modes

In addition to maximum power constraints, diesel generators are also restricted by minimum power generated ($\sim 30\%$ rated power). This is a barrier for increasing wind power penetration. To maintain system stability, there must be a minimum number of diesel generators operating to maintain the system's inertia (2 - 3 generators with existing loading). Therefore the wind power penetration is also limited by the minimum power generated by diesel generators.

2.4. Spinning reserve

Maintaining spinning reserve and responding to load variations is also an important technical issue for the hybrid system in Phu Quy island. At the moment, frequency control is governed by the diesel units. Diesel generators respond in the first place when there are load variations. The SCADA system detects the change in load and adjusts the power generated by wind turbines to ensure the predefined wind penetration. Due to the slow update duration of the SCADA system (in terms of seconds), wind turbines do not play a role in spinning reserve and primary response. This is an enormous barrier when trying to increase the wind penetration. As discussed in Section 2.1, enabling the frequency response

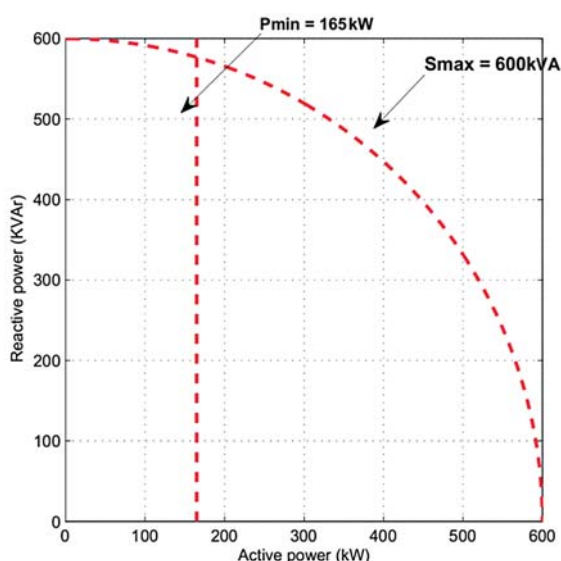


Fig.3. Power constraints of Cummins diesel generators

function of Vestas wind turbines would help wind power in providing primary response.

2.5. Minimum wind power

With wind speed over 7m/s, the minimum wind power generated by V80 generator is 500kW. When the wind speed increases over 17m/s, the minimum wind power generated is 800kW. At a certain load range, these restrictions limit the number of wind turbines operating since if all wind turbines are used this would violate the maximum allowable penetration.

2.6. Current operation scheme

The maximum allowed wind penetration at the moment is 50%. Considering all constraints given above, the operation scheme for the Phu Quy hybrid system is illustrated in Fig.4. This operation scheme has been developed based on the fact that diesel generators are responsible for all spinning reserve of the system ensuring high reliability. Results in Fig.4 show that 4 diesel generators are required at maximum load and 3 diesel generators are required at lower load.

If the wind penetration is not limited, in order to meet all technical constraints discussed above, the operation scheme is illustrated in Fig.5. The maximum wind penetration reaches 69% at peak load.

If comparison is made between the two operation schemes in Figs.4 & 5, it is clear that the number of diesel generators remains unchanged when the penetration level increases. This is due to the spinning reserve requirement. Nonetheless, diesel generators would have to operate at a low power factor in this case (approximately 0.6).

3. Overview of auxiliary technical solutions for the wind-diesel hybrid system

Auxiliary solutions to improve stability and efficiency in hybrid system can be classified into 3 categories as follows: auxiliary equipment to improve stability, low-load diesel generators to improve the penetration level and energy storage devices.

3.1. Auxiliary equipment to improve stability

Auxiliary equipment used for improving stability includes flywheels and dump-loads. Dump-loads have been used widely in wind powered systems in Alaska with the aim of consuming excess energy generated by wind tur-

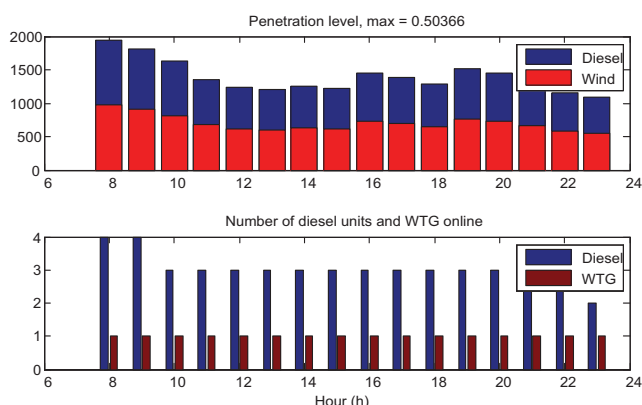


Fig.4. Current operation scheme in Phu Quy island

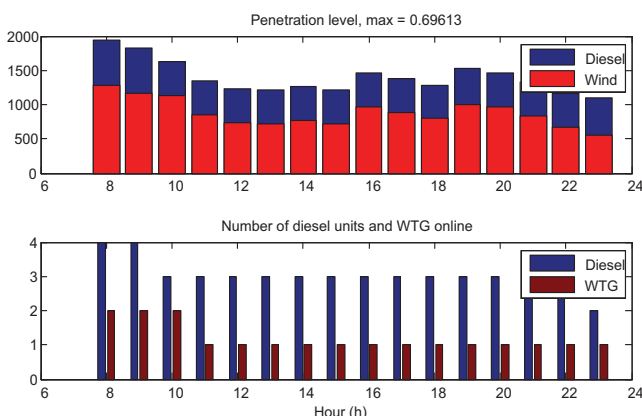


Fig.5. Operation scheme optimising wind penetration level and satisfying all technical constraints

bines. Dump-loads are generally equipped with a control system enabling fast response. Flywheels developed by Beacon [4] and ABB [5] consist of a rotating element which stores rotational dynamic energy and a bi-directional converter which allows either storing or releasing the energy of the flywheel. Advantages of a flywheel include very fast response (milliseconds) and high efficiency. However, the downside of the device is its limited storage capacity (order of kWhs) and it can only be used to adjust the frequency in a short duration.

The use of a flywheel does not increase the penetration level of wind power, it only improves the system stability and reliability. It is therefore difficult to quantify the financial benefits from a flywheel. On the other hand, the use of a dump-load may resolve the issue of minimum wind power (section 2.5), enabling higher penetration level at certain loading levels. As a consequence, a dump-load investment can be considered on the basis of having a better possibility to improve the wind power penetration.

3.2. Low-load diesel generator

Unlike conventional diesel generators which have to operate at a minimum 30% rated power, low-load diesel

generators are particularly designed to operate efficiently at 5% loading. This helps to reduce diesel operating costs, and at the same time utilising generators to govern the frequency, voltage and spinning reserve. The solution of using a low-load diesel generator is particularly useful for isolated hybrid systems of wind-diesel. This solution has been applied at several isolated systems such as Coral Bay (900kW wind power + 2240kW diesel), Delham (920kW wind power + 1,920kW diesel). The financial model for analysing an investment of a low-load diesel generator is relatively simple with low uncertainties.

3.3. Auxiliary energy storage devices

Energy storage devices include pumped-storage, fuel cells, batteries of different technologies integrated with power electronic converters [6]. One of many advantages of energy storage devices is the fact that almost all of wind energy can be exploited. Storage devices will store energy when wind power is larger than load demand and will release the energy when wind power ceases. In addition to their storage function, such devices can be integrated with control functionality to stabilise frequency, voltage and spinning reserve.

Each energy storage device has its own technical characteristics and features. Fuel cells normally have large capacity and energy. Super capacitors have good efficiency and fast response, however the amount of stored energy is limited. A common feature of storage devices is their high cost therefore an investment has to be thoroughly considered.

The possibility of using storage devices to store energy and make the most of wind energy depends on the correlation between wind power and load demand. With the present condition of load demand in Phu Quy island, the use of storage devices is not feasible because with 3 wind turbines of 2MW each, at all times, dispatchable power is around 2 - 2.1MW (30% of installed capacity). This power level is still higher than peak load in Phu Quy island, not to mention, the wind power needs to be limited due to the requirement of diesel operation to control the frequency and voltage. Preliminary calculations show that it would be inefficient to invest in a storage device on Phu Quy island in the near future.

Table 1 presents a qualitative comparison between different auxiliary solutions which can be applied to the Phu Quy power system. It is obvious that the low-load diesel generator solution meets reasonably well all technical requirements with a simple operation scheme. Hence this

solution should be carefully considered. Besides, the solution of using a compensation capacitor in combination with a dump-load also proves useful as it allows improving stability and penetration level and at relatively low costs.

4. Financial analysis for investment in a low-load diesel generator

A computational model for analysing optimal investment for an auxiliary solution is a complex one as it depends on a number of variable factors such as wind speed distribution, load growth, electricity tariff, restrictions on operation scheme, and reliability requirements, etc. With each auxiliary solution there is a separate computational model. A preliminary study on an investment of a low-load diesel generator has been conducted and the results are presented here.

The existing diesel generators and the wind turbines belong to two different owners. The investment analysis is carried out for the wind turbine owner, on the basis of maximising profit from increased penetration. The objective function of the model is as follows:

Maximisation (within the project lifetime): Revenue from selling electricity - fuel costs for low-load diesel generator - investment cost for low-load diesel generator.

Principal technical constraints consist of:

- Balancing active and reactive power.
- Constraints on generation characteristics of low-load and existing diesel generators (maximum and minimum power).
- Spinning reserve level.
- Maximum allowed penetration for wind power (maximum of 85% in the presence of a low-load diesel generator).

The optimisation model was calculated with different electricity tariffs and with assumptions of different load growth scenarios. Typical results are shown in Figs.6 and 7.

Fig.6 shows the optimal capacity for the low-load diesel generator for each electricity tariff and load growth with the project lifetime of 5 years. The diesel generator is responsible for 100% spinning reserve. The results clearly show that it is efficient to invest in a low-load diesel generator of 300kW. Once the tar-

Table 1. Comparison of auxiliary solutions

Auxiliary device	Frequency stabilisatio	Spinning reserve	Voltage Stability	Enhance penetration	Costs
Flywheel	+++	-	+	-	High
Dump-load	+	-	-	+	
Fuel cell	++	++	++	++	
Super Capacitor	+++	+	+++	+	High
LL diesel	++	+++	++	+++	
Capacitor + Dump load	+	-	+	+	Low

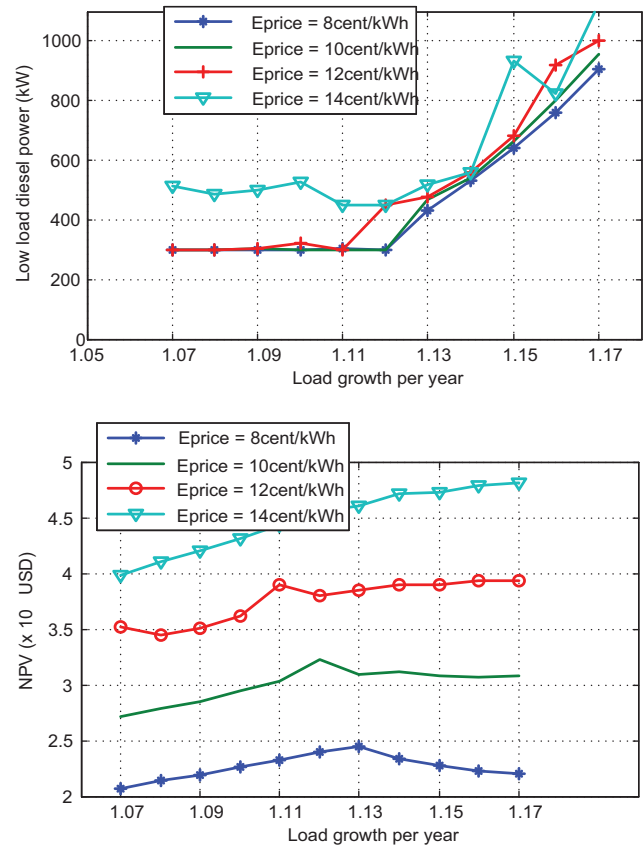


Fig.6. Investment analysis for a low-load diesel generator. Diesel generator responsible for 100% spinning reserve

iff reaches 14US cents/kWh, the investment proves cost-effective.

In case the diesel generator is responsible for 90% spinning reserve and all other assumptions are kept unchanged, the results are shown in Fig.7. In comparison with Fig.6, the financial benefits in this case become evident. Both analyses show that when the requirement for reliability can be compromised (higher risks), the investment for a low-load diesel generator yields a better return.

5. Conclusions

This paper reports technical and financial challenges that need resolving for the existing wind-diesel hybrid system in Phu Quy island.

In order to improve the system stability and reliability the following technical solutions are recommended:

- Operate 3 diesel generators at low and medium loads, 4 diesel generators at peak load in order to stabilise system frequency.
- Allow wind penetration level up to 70% on the basis of diesel generators covering all of the spinning reserve.
- Consider the possibility of using the frequency control function of V80 wind turbines in combination with the control function of the SCADA system to improve frequency stabilisation.

Regarding financial models to invest auxiliary equipment, it is concluded that:

- At present, a low-load diesel generator is considered to be a potential and feasible investment as this solution meets all technical requirements i.e. stability, spinning reserve, increase of wind penetration level and simple operation scheme.
- The solution of using a dump-load and a compensation capacitor is also attractive due to low cost invest-

ment and it may increase the wind penetration level in certain cases.

- Energy storage devices are considered not necessary at the moment due to low load demand as compared to the total installed capacity. Auxiliary storage equipment can be designed to improve stability and voltage controllability, however costs are high.
- In all cases the solution for the financial model to select appropriate auxiliary equipment depends on a number of factors such as electricity tariff, technical constraints and reliability requirements.

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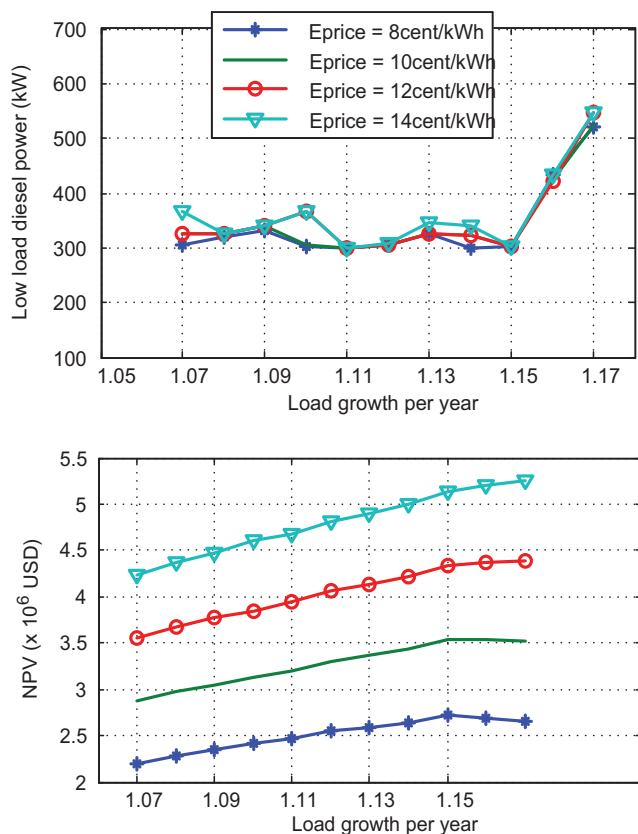


Fig.7. Investment analysis for a low-load diesel generator. Diesel generator responsible for 90% spinning reserve

ENVIRONMENTAL IMPACTS OF BIO-FUELS THROUGH EMISSION

Le Quoc Phong
Petrovietnam University

Summary

Air pollution is emerging to become a global problem. Emission from vehicles is one of the most dangerous pollutants. Use of bio-diesel is one of the means to reduce the emissions, particularly of particulate matter (PM) and nitrogen oxides (NO_x). The trend toward using bio-fuel as an alternative fuel will significantly increase in the near future as crude oil resources become depleted. This paper presents experimental results from a heavy-duty diesel engine using different bio-diesel fuels. Experimental bio-diesel fuels are rapeseed methyl ester (RME), blends of RME with conventional diesel fuel, gas to liquids (GTL), blends of GTL with conventional diesel fuel, O₂-diesel fuels called O₂-1 (O₂-diesel) in this experiment (a blend of ethanol and diesel fuel) and the blend of O₂-diesel and 5% RME called O₂-2 (95% O₂-diesel - 5% RME). The results presented here demonstrate that those bio-fuels not only represent a solution to counter the mounting scarcity of fossil fuels but also reduce the central elements of emissions.

1. Introduction

A substance in the air that can be harmful to humans and the environment is known as an air pollutant. Pollutants can be in the form of solid particles, liquid droplets, or gases. In addition, they may be natural or man-made. Exhaust gases from engines primarily contribute to forming air pollutants [1]. Therefore, finding methods which reduce emissions from vehicles to meet more stringent requirements of limiting air pollution are important and urgent tasks for researchers, manufacturers and regulators.

Besides technological solutions to reduce emissions from internal combustion engine, bio-fuels and their blend with fossil fuel have been used for a long time as they seem to be the most promising solution to emissions and the depletion of crude oil resources. Bio-fuel counterparts can be bio-gasoline (bio-ethanol), bio-diesel and bio-jet fuel. In practice, ethanol or the blend of ethanol and conventional fuels have usually been used for gasoline engine due to their suitable properties [1]. Therefore, researching the effects of the mixture of diesel fuel and ethanol as oxidised substance is an experimental goal. In this paper, the blend of ethanol and conventional diesel fuel called O₂-diesel (manufactured by Shell) or O₂-1 and the blend of O₂-diesel and 5% RME called O₂-2 are used to experiment because of the increasing trend of using diesel vehicles in transportation. In our experiments, the use of other bio-diesel such as RME (B100), the blend of RME and diesel fuel (10% RME - B10, 50% RME - B50), GTL (G100) and the blend of GTL and diesel fuel (50% GTL-

G50) are also studied. Experiments have also been carried out at different operating parameters such as full load, part load of engine and different EGR ratios (Exhaust Gas Recirculation - Exhaust gas is recirculated into the intake manifold of engine to reduce maximum flame temperature in the combustion chamber) to generally and deeply analyse the emission of bio-diesel.

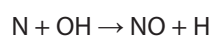
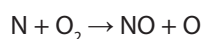
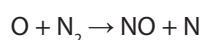
2. Emission and environmental and social health effects

The combustion of fuels with air containing O₂, inert gases and N₂ releases energy as heat in an exothermic reaction [1]. The heat released in internal combustion engine by hydrocarbon-based fuels such as gasoline and diesel fuel is determined by numerous incomplete reactions dependent on the compositions of the hydrocarbons in the fuel. Diesel fuel is composed of about 75% saturated hydrocarbons (primarily paraffins including *n*, *iso*, and cycloparaffins), and 25% aromatic hydrocarbons (including naphthalenes and alkylbenzenes) [1, 2]. Besides the main components such as CO₂, water vapour and N₂, pollutants such as carbon monoxide, unburned and partly burned hydrocarbons (HC-aldehydes, ketones, etc.) and NO_x also exist in exhaust gas of a diesel engine. These pollutants must follow national and international regulations. Pollutants are primarily produced by an interruption of the reaction chain when its dwell time in the combustion chamber is short. Hence, the equilibrium no longer exists. Inhomogeneities in the mixture caused by different air-fuel ratios (λ), combustion chamber wall effects and impurities and additives in the fuel also contribute to undesired by-products. Depending on the type of

the fuel and combustion process, solids may also be present as particle emissions. Unrestricted exhaust components produced by the thermal cracking of hydrocarbons and its by-products are increasingly attracting attention since they either are potentially hazardous or cause a discernible odour [3].

2.1. Nitrogen oxides (NO_x)

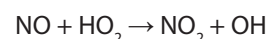
Unlike CO and hydrocarbon, NO_x , which consists of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), is a product of complete combustion. Nitrogen monoxide is the predominant nitrogen oxide produced inside an engine cylinder. The principal source of NO is the oxidation of atmospheric (molecular) nitrogen. However, if the fuel contains a significant amount of nitrogen, the oxidation of the fuel compounds containing nitrogen is an additional source of NO. It is generally accepted that the following are the principal reactions in the combustion of near stoichiometric fuel-air mixtures. Often called the extended Zeldovich mechanism, these reactions govern the formation (and destruction) of NO from molecular nitrogen [1]:



NO forms in both the flame front and post-flame gases. However, since combustion in engines occurs at high pressure, the flame reaction zone is extremely narrow ($\approx 0.1\text{mm}$) and the residence time within the zone is brief. Also, due to the cylinder pressures that increase during the combustion process the gases are compressed to a temperature higher than immediately after combustion. Thus, NO formation in the post-flame gases almost always dominates any formation of NO in the flame-front. Furthermore, the NO formation rate is a function of the gas temperature and fuel-air equivalence ratio in post-flame gases. In an engine, a noteworthy NO level can first be detected above around $1,900^\circ\text{C}$ [1]. Overall, more than 90% of NO_x emissions are nitrogen monoxide. Fuel nitrogen is also a source of NO by means of a different and not yet fully explained mechanism. The nitrogen in distillate fuels can exist as amines and ring compounds (e.g. pyridines, quinolines and carbazoles). During combustion, these compounds are likely to undergo some thermal decomposition prior to entering the combustion zone. Therefore, the precursors of NO formation are nitrogen-containing compounds with low molecular weights such as

NH_3 , HCN and CN. Detailed information on the kinetics of NO formation from these compounds is limited. A characteristic of NO is its reactivity with oxygen and particularly quick reactivity with ozone to form NO_2 . Pure NO does not irritate the lungs but if NO_2 remains unconverted, methemoglobin forms after resorbed by the respiratory tract. NO is an endogenous modulator of blood vessel tone and thus a well studied substance in terms of physiology and metabolism [1].

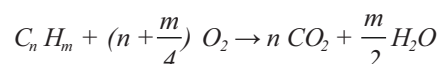
NO_2 has a pungent odour and a reddish brown color. A plausible mechanism for the persistence of NO_2 is:



Chemical equilibrium considerations indicate that NO_2/NO ratios should be negligibly small and NO_2 can be 10% of total exhaust of nitrogen oxides emissions [1, 2]. As a free radical, NO_2 is basically in a position to abstract hydrogen from fatty acids and thus to cause lipid peroxidation, which ultimately leads to a loss of function in biological membranes. In the presence of water, NO_2 develops as a cellular poison in the respiratory tract, through the nitric acid (HNO_3).

2.2. Hydrocarbon (HC)

Ideally, an internal combustion engine's combustion process corresponds to the following reaction [1]:



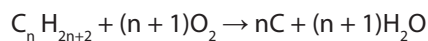
In practice, the combustion process does not produce carbon dioxide and water alone. Thus, combustion in an internal combustion engine is usually an incomplete process. As a result, incomplete combustion of the hydrocarbon-based fuel results in hydrocarbons or more organic emissions. The level of unburned hydrocarbon in the exhaust gases is generally specified in term of the total hydrocarbon concentration expressed in parts per million. Engine exhaust gases contain a wide variety of hydrocarbon compounds. Diesel fuel contains hydrocarbon compounds with higher boiling points and hence higher molecular weights than gasoline [1, 2]. Also, substantial pyrolysis of fuel compounds occurs within the fuel sprays during the diesel combustion process. Thus, the composition of the unburned and partly oxidised hydrocarbons in the diesel exhaust is much more complex than in the spark-ignition engine and extends over a larger molecular size range. Hydrocarbon constituents range from methane to the heaviest hydrocarbons that remain in the vapour phase in the heated sampling line (which is usually

maintained at about 190°C [2]. The levels of hydrocarbon emission from diesel engines vary widely depending on operating conditions.

So far it has not been easy to assess the direct impact of hydrocarbon emissions on humans. Hydrocarbon emissions are sometimes slightly relevant toxicologically (alkanes or alkenes etc.) and can also be carcinogenic (benzene) [2]. Hydrocarbons from engine emissions contribute to the development of summer smog.

2.3. Soot

Soot particles form primarily from the carbon in the diesel fuel and the incomplete combustion [1].



The formation process begins with a fuel molecule containing 12 - 22 carbon atoms and having an H/C ratio of about 2 and ends with particles that are typically a few hundred nanometres in diameter, composed of spherules with 20 - 30nm in diameters, each of which contains some 10⁵ carbon atoms and has an H/C ratio of about 0.1. Soot forms in the diesel combustion environment at temperatures between around 1,000 and 2,800K, at pressures of 50 - 100 bar and with sufficient air to fully burn all the fuel [2]. Solid soot particles form from a fraction of the fuel in milliseconds. Soot formation occurs in two stages. In the first stage, particles form. The initial condensed phase material is produced by the fuel molecules by means of oxidation and pyrolysis products. These products typically include various unsaturated hydrocarbons, particularly acetylene's higher analogues (C_{2n}H₂) and polycyclic aromatic hydrocarbons (PAH). These two types of molecules are considered the most likely precursors of soot in flames. In the second stage, particles grow. This involves surface growth, coagulation and aggregation. Surface growth, which generates the bulk of the solid-phase material, involves the attachment of gas-phase species to the surface of the particles and their incorporation into the particulate phase [2]. Surface growth reactions lead to an increase in the amount of soot but the number of particles remains unchanged. These stages of particle generation and growth constitute the soot formation process. In each stage, oxidation can occur, during which soot or soot precursors are burned with oxidising species to form gaseous products such as CO and CO₂. The real emission of soot from the engine will depend on the balance between these processes of formation and burnout [1, 2].

2.4. Particulate matter (PM)

Diesel particulates primarily consist of carbonaceous material (soot) generated in combustion, which have absorbed some organic compounds [1]. Most particulate material results from incomplete combustion of fuel hydrocarbons, but also from the lubricating oil. Other sources are hydrocarbon compounds (some of which are bound to soot) and a few sulfates in the form of aerosols. In a combustion engine, the development of particles is related to the development of soot, which in turn basically depends on the local temperature of the zone the fuel enters and a low oxygen supply. According to the Acetylene Theory, the combustion of different hydrocarbons runs through several intermediate substages such as cracking and dehydration. This increases the share of carbon molecules until the first particle with a diameter larger than 0.01µm develops, around which so-called primary particles coagulate to form larger units with diameters from 0.01 - 0.08µm (forming secondary particles). Their large specific surfaces enable uncombusted and partly combusted hydrocarbons, especially aldehydes, to bond to the secondary particles. When combustion occurs, the secondary formation phase is soot reoxidation governed by the dwell time and oxygen concentration. A specific problem of diesel engines is the conflict between particles and NO_x. The conditions for low particle formation and low hydrocarbon emissions (achieved with higher temperatures) conflict with the preconditions for low nitrogen oxide emissions. Therefore, attention is concentrated on the secondary formation phase of soot reoxidation. Soot reoxidation necessitates a large amount of mixture formation energy in the last phase of combustion. This can be attained by a specific swirl and tumble in the combustion chamber, higher injection pressure and a faster injection rate at the end of the injection process. Unfortunately, these conditions are prerequisites to high NO_x emissions.

Numerous environmental studies have concluded that increases of particle concentration in the air correlate with increases in the number of patients with respiratory and circulatory illnesses. Also found is a link between the risk of lung cancer and particles as well as ozone and sulfur dioxide. In general, particle emissions have a negative impact on human health, especially in particularly sensitive individuals, e.g. children, the elderly and invalids.

2.5. Carbon monoxide (CO)

Carbon monoxide is likewise a product of an incom-

plete combustion process. CO emissions from internal combustion engines are primarily controlled by the air fuel ratio. CO concentrations in the exhaust of fuel-rich mixtures steadily increase as the air fuel ratio decreases, i.e. as the amount of excess fuel increases. Since the fuel-air mixture must be enriched when an engine is cold, CO emissions during engine warm-up are much higher than emissions in the fully warmed-up state.

Carbon monoxide is a colourless and odourless gas and attaches itself to hemoglobin 250 times more strongly than oxygen. As CO concentrations increase in inhaled air, the suppression of oxygen induces symptoms from suffocation to death. Acute poisoning occurs above 2,000ppm. All in all, CO emissions from internal combustion diesel engines are insignificant [1, 3].

2.6. Unregulated emission components

Important unregulated exhaust gas components in untreated exhaust from diesel engines are cyanide, ammonia (NH₃), sulfur dioxide (SO₂) and sulfates. Of the specific hydrocarbons, methane, ethane, ethene, ethine, benzene and toluene are of particular interest. Of the PAH, phenanthrene, pyrene, fluorene, fluoranthene and anthracene predominate and in that order. The concentration of these components is at least six times higher than that of other individual PAH substances and forms

about 90% of the PAH [3]. The components cited are formed from trace substances in the fuel, in the lubricant and, to a degree, from secondary reactions in the exhaust system.

Combustion exhaust gases contain a multiplicity of different toxic elements. The bulk of the over 150 PAH substances identified are mutagenic and carcinogenic. Many studies have been carried out on the influences of diesel engine emissions on the health of humans and the environment [2, 3]. In 1978, an Ames Test (Salmonella Microsome Test) performed by Huisingh demonstrated for the first time the capability of diesel engine emissions to cause genetic damage. Since then, many further studies have confirmed these findings [3].

In this paper, main emissions from diesel engine such as hydrocarbon, NO_x, PM (illustrated through soot or FSN- Filter Smoke Number) with different bio-fuels and the blends have been evaluated. FSN have been measured at full load with different speeds (from 600rpm-idle to 2,400rpm-maximum speed). In addition, FSN and other emissions such as hydrocarbon and NO_x have been tested at part loads (1,100rpm - 213Nm and 425Nm), full load (1,400rpm - 850Nm) with different EGR (Exhaust Gas Recirculation- the effective method to reduce NO_x emission in diesel engine) ratios (0%, 9% and 27%).

Table 1. Properties of O₂-diesel (ethanol-diesel blend) [5]

Parameters	Testing procedure	Unit	DIN EN 590	Diesel fuel (DF)	O ₂ -diesel
Heat value	DIN 51 900-2	MJ/kg	approx. 42	43.866	42.360
Cetane number	DIN EN ISO 5165		min. 51	55.5	54.8
Cetane index	DIN EN ISO 5165		min. 46	54.6	52.8
Density in 15°C	EN ISO 12185	g/cm ³	0.820 - 0.845	0.8276	0.8252
PAK	DIN EN 12916	% (m/m)	max. 11	2.0	1.9
Sulfur content	EN DIN 51400-10	mg/kg	max. 10	8	3
Flash point	DIN EN 22719	°C	> 55	56.9	12.9
Coke residue (of 10% distillation residue)	DIN EN ISO 10370	% (m/m)	max. 0.30	0.004	0.08
Water content	EN ISO 12937	mg/kg	max. 200	130	250
Oxide ash	DIN EN ISO 6245	% (m/m)	max. 0.01	0.001	0.004
Total contamination	DIN EN 12662	mg/kg	max. 24	27.3	27.8
Copper corrosion (3 hours at 50°C)	EN ISO 2160		1	1	1
HFFR Lubricity with 60°C	DIN EN ISO 12165-1	µm	max. 460	317	284
Viscosity in 40°C	DIN 53015	mm ² /s	2.00 - 4.50	2.71	2.03
Distillation					
% [V/V] - 250°C	DIN EN ISO 3405	Vol. -%	< 65	41	45
% [V/V] - 250°C		Vol. -%	min. 85	94	95
95% - Point		°C	max. 360	352.9	353.3
Fatty acid methyl ester content	EN 14078	% (V/V)	max. 5	0.17	0.16
Cold filter plugging point (CFPP)	DIN EN 116	°C	max.0	-8	-7

3. Experimental bio-diesel

3.1. O₂-diesel (Ethanol diesel fuel) or O₂-1 (as called in this experiment)

O₂-diesel that is used in this study is supplied by Shell Company. The analysis of O₂-diesel used for the experiments in this study was performed at the University of Rostock. Table 1 presents the properties of experimental O₂-diesel.

O₂-diesel fuel is a mixture that consists of the following components [5]:

Water-free ethanol: 7.7% Vol.

Diesel fuel: 91.6% Vol.

Additive 2EHN: 0.2% Vol.

Additive O2DO5: 0.5% Vol.

The additive 2EHN with 0.2% Vol. was used to enhance the cetane number for a number of reasons. One of them is that a small amount of water can be introduced into the fuel system because ethanol has an affinity to water (the experimental ethanol diesel blend had a water content of less than 0.5%) and because blend levels of up to 15% are often desired. One way to achieve this is to use additives. Two common types of additives are surfactants and co-solvents. O₂-diesel with these additives are very stable. Co-solvents have an immediate polarity between ethanol and diesel fuel and act as a bridging agent to produce a homogeneous blend.

Experiments were carried out with O₂-1 and the blend of O₂-diesel and 5% RME (called as O₂-2 in this experiment).

3.2. Rapeseed methyl ester (RME)

RME is manufactured from rapeseed. RME has been used as bio-diesel fuel in Europe for a long time. Since the 2,000s, diesel fuel, including 5% bio-diesel (RME), is used in practice [4]. Therefore, experiments are being conducted with different blending ratios of diesel fuel and RME, for example 100% RME, B50 (50% RME), B10 (10% RME). Table 2 show the properties of experimental RME.

Table 2. Properties of RME [5]

Parameters	Testing procedure	Unit	Diesel fuel	RME
Heat value	DIN 51606	MJ/kg	43.866	37.6
Cetane number	DIN EN ISO 5165		55.5	45 - 59
Density at 15°C	ISO 3675	g/cm ³	0.8276	0.875 - 0.900
Sulfur content	ISO 4260	mg/kg	8	9 - 12
Flash point	ISO 2719	°C	56.9	110
Coke residue (of 10% distillation residue)	DIN EN ISO 10370	%	0.004	0.05
Water content	DIN 51606	mg/kg	130	300
Oxide ash	DIN EN ISO 6245	%mass	0.001	0.01
Total contamination	DIN EN 51419	mg/kg	27.3	20
Copper corrosion (3 hours at 50°C)	EN ISO 2160		1	1
Viscosity at 40°C	ISO 3104	mm ² /s	2.71	3.5 - 5
Cold filter plugging point (CFPP)	DIN EN 116	°C	-8	-9 to -7

Table 3. Properties of GTL [5]

Parameters	Testing procedure	Unit	Results
Density	EN ISO 12185	g/cm ³	0.7853
Viscosity at 40°C	DIN EN ISO 3104	mm ² /s	3.5871
Cloud point	DIN EN 23015	°C	0
Cold filter plugging point (CFPP)	DIN EN 116	°C	-3
Sulfur content	DIN 51400 T11	mg/kg	< 5
Heat value	ASTM D240	MJ/kg	44,398
Cetane number			74
Distillation	DIN EN ISO 3405		
Boiling point		°C	202.3
T10		°C	244.7
T50		°C	295.2
T90		°C	340.9
Boiling end point		°C	351.3
Residue		% v/v	2.0
Flash point	ASTM D93	°C	89
Carbon to hydrogen ratio			2.13
Aromatics	ASTM D5186	mass %	1.4
Gum content	ASTM D381	mg/100ml	5.9
Ash	ASTM D482	mass %	< 0.001
Carbon residue	ASTM D524	mass %	0.03

3.3. Gas to liquids (GTL)

Produced by the Shell Middle Distillate Synthesis (SMDS), GTL is one of the new alternative fuels used for diesel engines without any modifications. The Lab of Shell Global Solutions (Deutschland) GmbH in Hamburg performed the testing of the GTL properties. Table 3 presents the test results.

Experiments are conducted with different blending ratios of diesel fuel and GTL, for example 100% GTL, G50 (50% GTL).

4. Effects of bio-diesel and these blends on emission

Research was carried out on a DEUTZ BF6M 1013 EC

heavy-duty engine with different operating points. The DEUTZ BF6M 1013 EC is a four-stroke direct injection engine with six in-line cylinders and turbocharger and are retrofitted with exhaust gas regulations (EURO II). Experiments have been carried out in the laboratory of the Institute of Mobile Systems, University of Magdeburg, Germany. Experiments have also been conducted at the different operating points of engine such as full load, part load and different EGR ratios.

At full load of engine, diesel fuel, O₂-1, B10 (10% RME - 90% DF), B50 (50% RME - 50% DF), B100 (100% RME) and GTL (G100) were tested. At other operating points of the engine, diesel fuel, O₂-1, O₂-2, B10, B50, B100 (RME) were G50 (50% GTL-50% DF), G100 were experimentally examined.

Besides the different operating points, experiments were also carried out at different EGR (Exhaust Gas Recirculation) ratios. EGR is the effective method to reduce NO_x emission in diesel engine. EGR has not been analysed in detail in this paper.

4.1. FSN

Bio-diesel and their blends point to better emissions trends, especially the FSN at full load (Fig.1). The FSN decreases by roughly 40% with B100 and at least 21% with O₂-diesel and B10. The FSN falls around 38% with B50. GTL 100% has a lower FSN than O₂-diesel, except at speeds above 1,800rpm. Compared with diesel fuel, GTL 100% decreases by about 6.4% in the minimum point (2,200rpm) and around 22% in the maximum point (800rpm). All the alternative fuels and their blends have generally been found to decrease the FSN.

Experimental results also confirmed that fuel temperatures had less impact on engine torque and fuel consumption (B₀ g/h) when RME, G100 and diesel fuel were used than when O₂-diesel was used. The temperatures of RME, GTL and conventional diesel fuel were similar under most operating points and conditions. By contrast, the temperature of O₂-diesel significantly influences engine torque and fuel consumption. Experimental results indicate the engine runs unstably when the temperature of O₂-diesel is around 55°C (the same working temperature as diesel fuel, GTL fuel and RME). When the temperature increased from around 30 - 55°C, engine torque changed approximately 10% and B₀ approximately 8.3%. The evaporation of ethanol in O₂-diesel and its lower boiling temperature range are responsible for these effects. Experimental results also confirmed the engine ran stably

when the temperature of O₂-diesel was approximately 30°C. Therefore, this was the temperature maintained in experiments with O₂-diesel.

Fig.2 presents decreasing trends of FSN for all alternative fuels and different operating modes of engine, compared with diesel fuel, except when the EGR is 27% and except for G100 and G50. The changing percentages are largest with B100 and lowest with GTL, its blend and B10. The maximum changing percentage is over 60% with B100 at lower part load (1,100 1/min - 213Nm). When the speed is the same (1,100 1/min), EGR is 9% and engine load increases from 213 - 425Nm, the changing percentage decreases from over 50% to over 40% with B100 and increases modestly with O₂-diesel.

4.2. NO_x

Compared with diesel fuel, the largest increased percentages are always found with B100 and the strongest decreased percentages usually occur when G100 is used (Fig.3) because RME has the lowest heat value, the highest density, highest injection mass and highest injection pressure not only compared with diesel fuel but also other alternative fuels. Therefore, the combustion rate and combustion temperature peak are highest with RME.

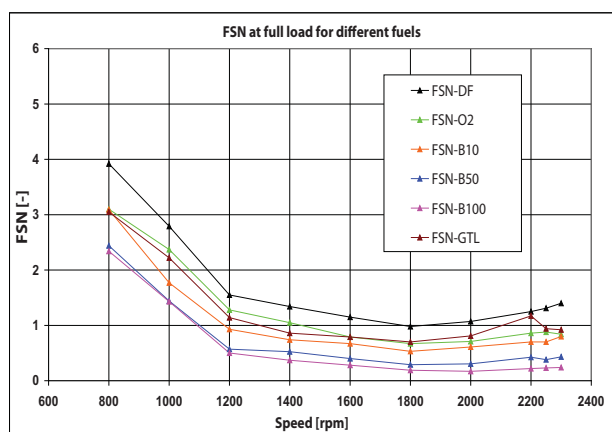


Fig. 1. FSN for different fuels [5]

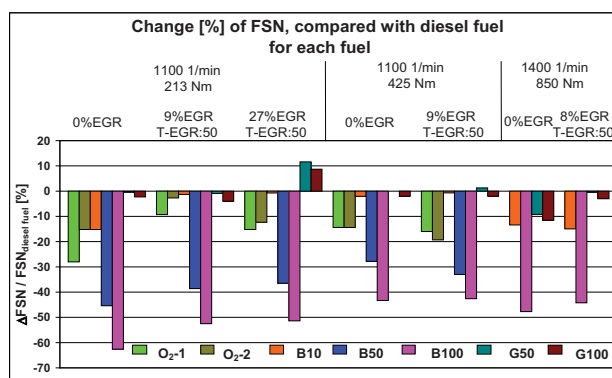


Fig. 2. Change of FSN in percentage, compared with diesel fuel [5]

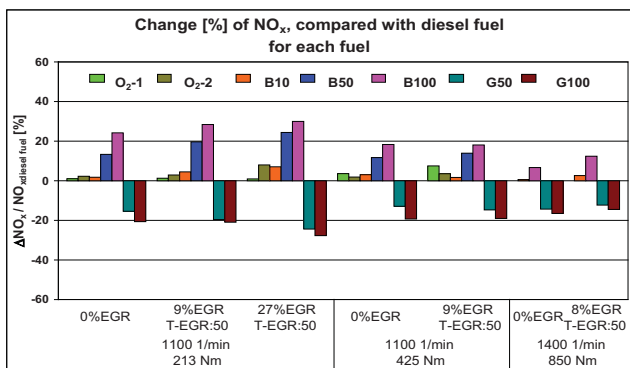


Fig.3. Change of NOx in percentage, compared with diesel fuel

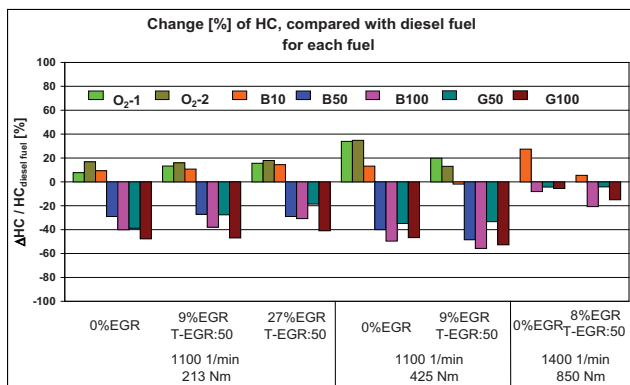


Fig.4. Change of hydrocarbon in percentage, compared with diesel fuel

Compared with diesel fuel, the largest increased percentage is over 30% with B100 when EGR is 27%. The strongest decreased percentage is over 20% with G100 under the same conditions (Fig.3). RME blends have lower changing percentages than neat RME and G50 has lower changing percentages than G100. Changing percentages of NO_x emission of different fuels are smaller when engine load increases. When the speed is maintained (1,100 1/min), there is no EGR and the engine load increases from 213 - 425Nm, the changing percentage of NO_x with B100 drops from 24 - 18% and is around 6.7% when the engine runs at maximum torque (1,400 1/min - 850Nm).

Generally, GTL and the blend always present a decreasing trend of NO_x emission. In contrast, other alternative fuels and their blend such as RME and O₂-diesel show an increase of NO_x emission. Therefore, a combination of EGR and bio-fuel is used for reducing NO_x emission in diesel engines.

4.3. Hydrocarbon

Hydrocarbon emission changes significantly with B100, G100 and G50 (Fig.4). Maximum changing percentages (over 50%) occur with B100 and G100 when the EGR ratio is about 9% and the engine runs at higher part load. Compared with diesel fuel, the maximum increased per-

centages are over 20% (about 8ppm) with B10 at maximum torque and without EGR and over 30% (over 30ppm) with O₂-diesel at higher part load and without EGR.

Like NO_x emission, hydrocarbon also increases when engine runs with GTL and O₂-diesel. Higher increase occurs with higher load of engine.

5. Conclusions

Emissions decrease with most bio-fuels. Changing percentage of emission increases with higher content of bio-fuel that is mixed with conventional fuel. Combination of other methods such as EGR, load, EGR temperatures, and bio-fuels are positive means for decreasing pollutants from the exhaust gas of an diesel engine. This confirmed that use of bio-fuels or the blend of bio-fuels and conventional fuels will meet stricter future requirements for emissions which pollute the environment. The experimental results also confirmed that step-by-step increase of the percentage of bio-fuel in the blend is a suitable practical method in applying progress. Finding and applying bio-fuels will be important future goals for the world. Protecting and encouraging bio-fuel use through tax and other policies will be required for a green planet in the future.

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