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# **Natural-gas-fuelled engines for emergency operation**

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## **Summary**

Natural-gas-fuelled engines are increasingly used all over the world to drive electric generators in distributed electricity applications. Often, these are cogeneration plants where also the heat released is utilised. A reliable supply of high-quality electricity as well as fuel conservation and low electricity costs are very important. In case of grid failure, gas-engine-driven generators can be used in island operation to generate the locally required electricity. With modern gas engines equipped with the proper fuel-supply control strategy, such generators have an excellent frequency stability and load-step response. This paper explains the background of the reaction of modern gas engines to step loads in island mode. The paper also compares the properties of such engine-driven generating sets with the requirements in ISO 8528.

## **Introduction**

Natural gas is rapidly gaining importance as an energy supplier to the world (ref. 1). It is a fuel with a relatively low specific emission of CO<sub>2</sub> and it accommodates combustion processes with low NO<sub>x</sub> emissions. The easy and low-cost transportation of natural gas via pipelines facilitates its use in local applications such as domestic boilers and installations for cogeneration of electricity and heat. With modern cogeneration installations, a maximum utilisation of the fuel energy can be reached with a minimum environmental impact. Reciprocating-engine-driven generators have the advantage of short lead times and offer a high flexibility in power capacity. The investments costs in engine-driven generator sets and cogeneration installations are low compared with many alternatives, especially when the high fuel efficiency is taken into account. With the increasing importance of natural gas, it is expected that natural-gas-fuelled distributed generation with optional cogeneration will become more widespread all over the world.

Electricity is playing a vital role in the economy; it can be seen as the motor of quality manufacturing and innovation. An affordable and reliable supply of high-quality electricity is of utmost importance for a sustained wealth and comfort level. In this

connection, distributed generation is an excellent tool for attaining a high local supply reliability as well as low transportation and distribution costs of electricity (ref. 2). The installation of cogeneration plants at sites of major consumers can ensure that electricity is available even when central power production fails. An engine-driven generator can be switched to the island mode and supply the local user with electricity (and heat). That means that vital processes using electricity can be continued and that information and communication technologies can still be used.

The quality of the locally produced electricity should comply with the requirements for frequency and voltage stability. Also the waveform should be acceptable. The International Standard ISO 8528 (ref. 3) gives a comprehensive overview of the specifications for electricity generators in island mode with respect to long-term stability and step responses. The general feeling in the past has been that natural-gas-fuelled reciprocating engines were less suitable for island operation than e.g. diesel engines. This paper will show however that gas engines equipped with modern electronically controlled gas-admission valves per cylinder do have an excellent step response. The authority of the control system over the fuel supply is so good that satisfaction of ISO 8528 does not raise any problems.

### Initial response of a generator set to a load step.

Traditionally, generators in island mode are frequency, or speed, controlled. The speed controller compares the real, measured, value of the speed with the desired value (see figure 1). Any speed deviation  $\epsilon$  is detected and used to generate a command to adapt the fuel flow to the prime mover so that the measured speed will be restored to the desired value. For the stability of such control systems, use has to be made of control algorithms set according to the rules of control theory. In practice, there is always some time lag between the detection of a speed deviation and the response of the driving engine. Therefore, the very first part of the step response of a speed-controlled generating set only depends on the ratio of the power difference caused by the load step and the rotational energy of the set.

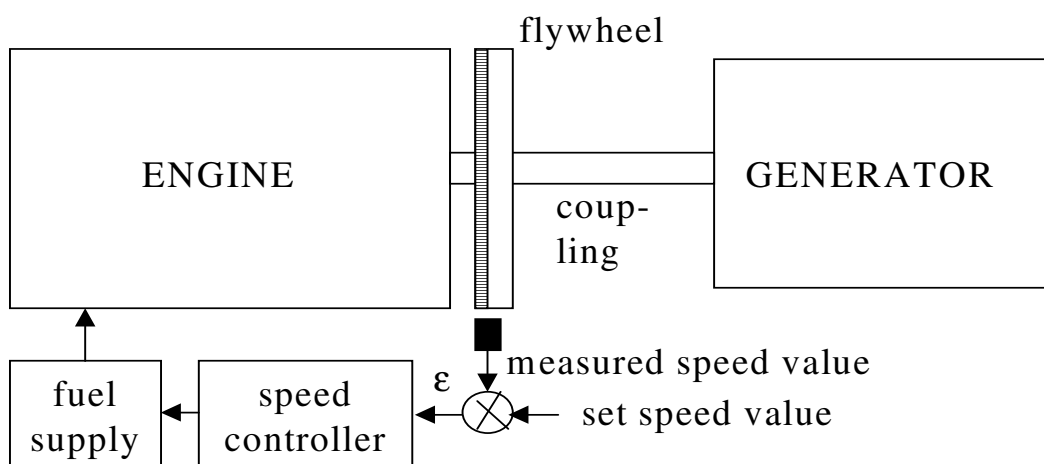


Figure 1: Speed control of a generating set.

The inclination of the initial speed increase or decrease due to a load step can be calculated from the inertia of the rotating mass of the generating set and the amount of load change. It can be shown that the initial speed change equals:

$$\frac{dn}{dt} = - 3600 \Delta P / (4 \pi^2 I n), \quad (1)$$

in which:  $n$  = speed (rpm)  
 $\Delta P$  = load step (watt)  
 $I$  = moment of inertia ( $\text{kgm}^2$ ).  
 $t$  = time (s).

As an example, a generating set with a moment of inertia of  $1000 \text{ kgm}^2$  running at 1000 rpm will initially show a speed decline of 182 rpm/s after an electric load increase from 0 to 2 MW. Figure 2 illustrates how such an installation will slow down in speed when nothing will be changed to the fuel input of the driving engine. Three different cases have been distinguished. The first one is an example where the electric generator has been equipped with voltage control, and that is normally the case. With an idealised voltage control, the output voltage of the generator is independent of the running speed so that with a constant active load (a resistive load) the electric load remains the same. In this case, the set will be at full standstill within 2.5 seconds. If no voltage control is used,

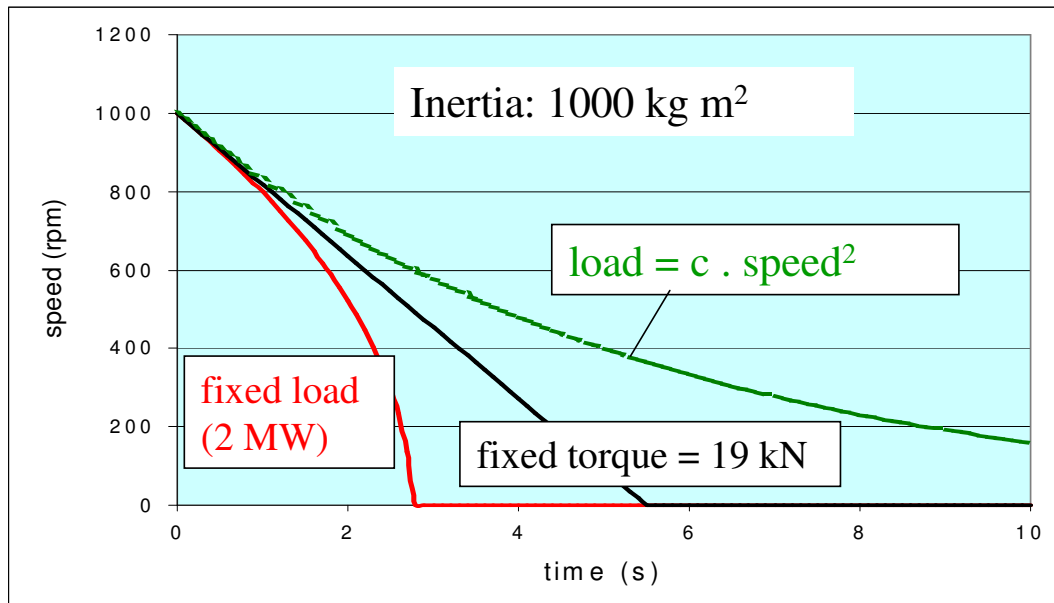


Figure 2: Generating unit speed decline with an initial step load of 2 MW.

the generator voltage is roughly directly proportional to the running speed and the power requirement will decrease in proportion with the running speed squared. In that case, the set will continue to run on a low speed for quite a while. In the third case, where the torque is fixed to the value associated with the 2 MW at rated speed, the speed will linearly drop till the unit comes to a standstill after 5.5 seconds. In reality, some

deviations will occur due to practical implications, but figure 2 is intended to give the general trend.

Figure 2 helps to understand the need for a quick reaction of the driving engine. If in the example of figure 2 the engine fails to produce the additionally required 2 MW within 0.5 s, the running speed and the frequency will have dropped by more than 10%, which means that the transient frequency deviation limit of class G2 of ISO 8528 for diesel engines has been exceeded. For spark-ignition engines, 20% speed deviation is allowed in class G2.

### Response of a spark-ignition gas engine to a change in energy supply.

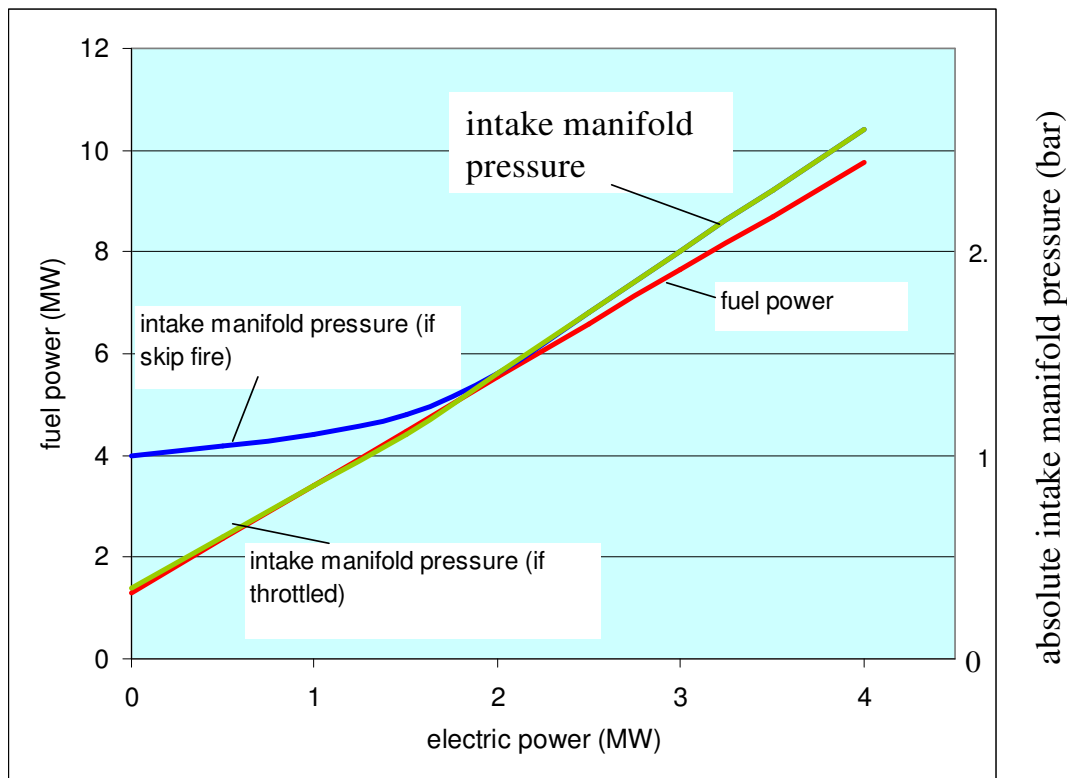


Figure 3: Air-to-fuel-ratio control with a turbocharger and a throttle valve or skip fire.

Modern stationary natural-gas-fuelled spark-ignition engines are equipped with turbochargers to ensure a high specific power capacity (bmep) and a high shaft efficiency. Without turbochargers, stationary engines are hardly economically competitive. To avoid cylinder overheating, combustion knocking and excessive NOx production with highly loaded cylinders, the engines are using lean mixtures. This means that substantially more air is used in the cylinder process than theoretically required for complete combustion. A mixture of fuel gas and air having the theoretically required amount of air is called a stoichiometric mixture with an air-to-fuel ratio  $\lambda$  of 1. A mixture with 100% extra air has by definition a  $\lambda$  of 2. Mixtures leaner than lambda

2.2 are very difficult to ignite. Mixtures leaner than  $\lambda = 1.6$  need already a rich-running prechamber or a diesel pilot to ensure proper ignition. In the higher load range of engines, a proper matching of the turbocharger and its associated waste gate or dump valve can create the desired air-to-fuel ratio. In the low load range, when the turbocharger is hardly active, either the air flow to the engine cylinders has to be reduced via a throttle valve or 'skip firing' has to be used to ensure that an ignitable mixture is present in the cylinders. Figure 3 is illustrating how the desired air-to-fuel ratio can be provided for in the full load range of a modern turbocharged engine.

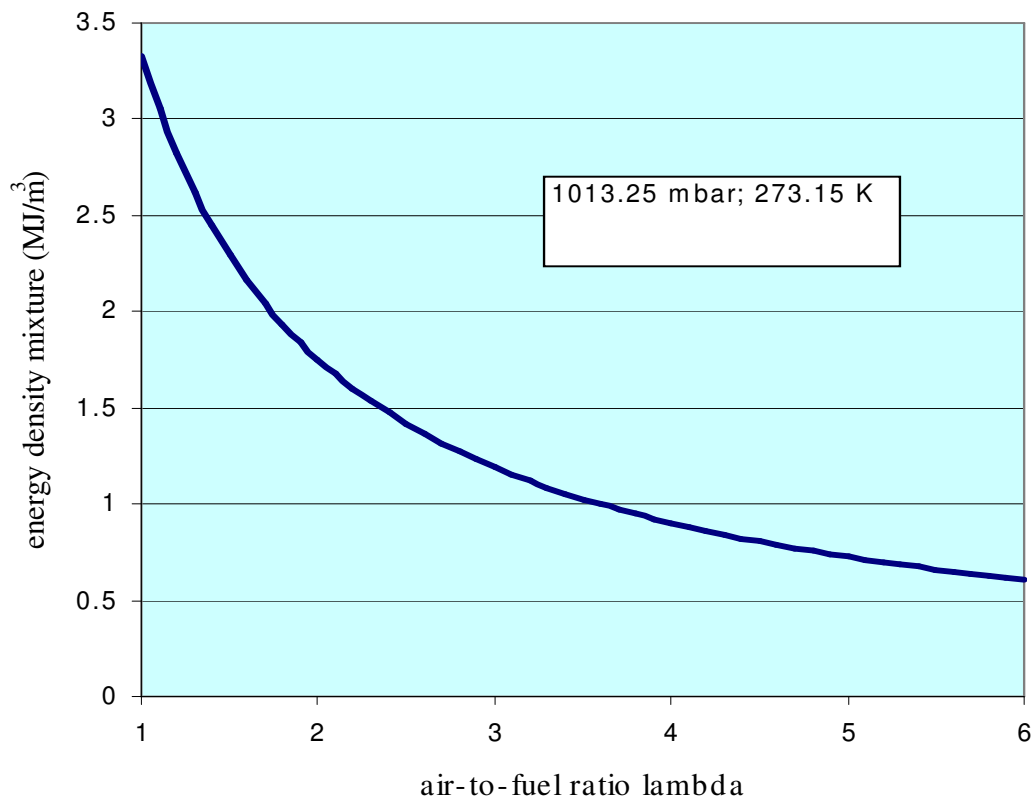


Figure 4: The energy density of a mixture of Groningen gas and air for standardised conditions (1013.25 mbar, 273.15 K).

The volumetric energy content of the mixture of fuel gas and air is the major factor determining how much work will be produced by an active cylinder. The other factor is the fuel energy into work conversion efficiency which is mainly determined by the compression ratio and the process losses (ref. 4). The volumetric energy content of a mixture depends on the air-to-fuel ratio, the calorific value of the fuel gas and the pressure and temperature of the mixture. Figure 4 gives the volumetric energy content of a mixture of Groningen gas and air as a function of the air-to-fuel ratio for standardised conditions of 0 °C and 1013.25 mbar. From figure 4, it can be seen that the energy density of a mixture with lambda 1.0 is a factor 1.9 higher than for lambda 2.0. The sensitivity of the energy density to lambda is the highest near lambda 1. Doubling the absolute mixture pressure for the same lambda and temperature will naturally double the

energy density. Changes in energy density due to changes in temperature are inversely proportional to the absolute temperature.

If the generator load increases, the engine has to produce more power to maintain the desired running speed. For engines using a throttle valve and a carburettor (ref.5), the throttle valve is opened to allow more mixture to enter the engine manifold. The carburettor has to ensure that the air-to-fuel ratio is maintained at the desired value. In many cases, the response time of the pressure regulator of the carburettor makes that for a short time the mixture will be leaner than desired. Filling up the intake manifold to the pressure required for the new load also takes time, up to several engine revolutions. Subsequently, the engine has to suck in the mixture, compress it and ignite it. It will take at least three additional engine shaft revolutions before all cylinders respond to the increase in mixture pressure. For a fixed air-to-fuel ratio, the authority of the throttle valve on the engine power is quite high in the lower load range. The absolute intake manifold pressure of a modern turbocharged engine with throttle-valve control is about 0.3 bar at zero load and about 1 bar at 30% load (compare figure 3). That means that a load step from 0 to 30% can easily be taken by such a system, at least in theory. For the load steps in the higher load range, the turbocharger characteristics determine how much pressure drop is available over the throttle valve. That pressure drop in turn determines the load-step size that the engine can accommodate in that load range. The lag of the turbocharger in responding to the new condition makes that the allowed step load is much smaller at higher loads than at lower loads. For engines equipped with electronically controlled gas admission per cylinder, the 'skip fire' option in combination with temporary enrichment of the mixture offers the better alternative for load steps.



Figure 5: The solenoid operated gas-admission valve (Courtesy of Woodward).

Figure 5 shows an electronically controlled gas-admission valve for larger gas engines. The response time of such valves to an opening or closing command is less than 3 ms, which corresponds to 18 degrees crank angle for a 1000 rpm engine. That leaves

sufficient space for controlling the gas flow to the individual cylinders during the intake stroke. The actual opening time in combination with the density of the gas and the pressure drop over the valve determine the gas flow. With modern electronic control systems, such as the WECS system developed by Wärtsilä, close control of the amount of fuel gas supplied to each engine cylinder is possible. From the fuel flow and the absolute air-manifold pressure, the WECS system can instantaneously determine the air-to-fuel ratio of the mixture provided for each cylinder. Temporary enrichment of the mixture for the cylinders can be easily and rapidly achieved, resulting in an excellent step response.

### Response of an engine-generator combination to a step load

The typical response of a reciprocating engine-generator combination to a step load is given in figure 6. The initial speed drop (indicated by the line A) is primarily determined by the ratio of the power increase and the rotating energy of the engine-generator combination (see equation 1). However, also the voltage control system of the generator can play a role in this initial response. If the voltage control is excessively rapid or even overshooting, this might unnecessarily add to the burden on the generating unit. As soon as the command for providing extra mixture to the cylinders is given, the engine will respond but always with a time lag resulting from the typical four-stroke mixture compression cycle. The mixture preparation method also affects this process, as has been explained in the previous paragraph. In this region, indicated by 'B', the engine tries to adjust to the new load situation. In region 'C', the speed change becomes zero which means that the newly established cylinder conditions provide exactly the power required

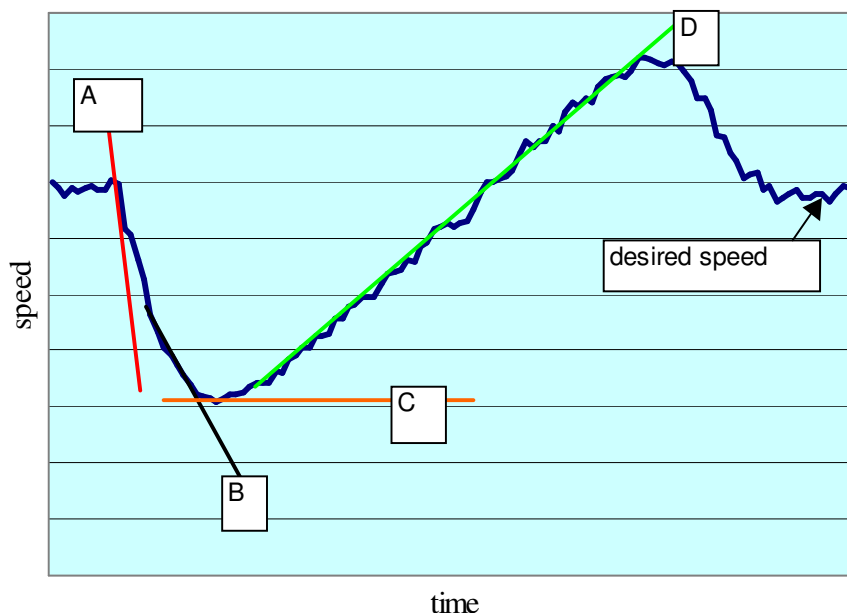


Figure 6: An example of a response of an engine-generator combination to load changes

to drive the generator at the new load. The work per cycle is in this case slightly higher than in case the engine would run exactly at the rated speed: less cylinder cycles per time unit are available to produce the required power. Subsequently, additional power is required to bring the running speed back to the desired value. The inclination of the speed curve is a measure of the additional power required for this ('D'). If an energy drop of the rotating inertia of 300 kJ has to be restored in 3 s, temporarily an additional engine power of 100 kW is needed. Apart from the negative consequences of a frequency drop, this is an additional reason to keep the speed drop as small as possible. As soon as the engine reaches its rated speed, the mixture supply to the engine can be reduced to the amount required in the new steady state condition. However, due to the mechanisms explained earlier, each engine has some delay time in handling the new situation which takes a minimum of three shaft revolutions. The overshoot after crossing the rated speed (excessive in this example) finds an additional cause in the 'integral' (= I) action of the speed controller. Finally, the engine-generator combination reaches its desired speed.

One might argue that a larger moment of inertia is of benefit for reducing the speed decrease or increase during load changes in the island mode. This is true to some extent, but an increased moment of inertia also means that it becomes more difficult to detect speed changes. A large amount of rotating energy tends to camouflage load steps. Additionally, with more inertia the total reaction time required to restore the running speed to the desired value will be longer. For an optimum response, the moment of inertia of the set has to be matched to the running speed and to the chosen control strategy.

Responding to load changes via detection of the running speed of the installation is based on feedback control and subsequent reactions of the engine. An alternative is a primary response via sensing of the instantaneous load (feed forward control) and adjusting the fuel flow to the engine according to the actual power demand. The exact speed is then adjusted in a secondary reaction. Multivariable control methods can easily take care of this task. The Wärtsilä method of supplying mixture to the cylinders via the individual gas admission valves is especially suitable for an exact matching of the fuel flow to the new power demand. Only the typical time lag of the four-stroke cycle can never be avoided. The total response is quicker and less deviations from the desired frequency will occur than with carburetors and throttle valves.

The advantages of controlled gas-admission valves per cylinder for an adequate step response will be explained once more with an example. A reciprocating engine with a rated brake-mean-effective pressure of say 18 bar running at its rated speed has at zero load a fuel consumption due to friction losses, heat losses and auxiliaries of about 12 to 13 % of that at 100% load. The absolute manifold pressure of such an engine is close to 2.6 bar at full load and that renders an air to fuel ratio  $\lambda$  of say 2.1 (see also figure 3). The specific energy content of the mixture at full load equals  $1.7 \times 2.6 \times 273.15 / (273.15 + 60) = 3.62 \text{ MJ/m}^3$  for a presumed mixture temperature of 60 °C. The  $1.7 \text{ MJ/m}^3$  has been taken from figure 4 which gives the energy density for standard conditions. At zero load, say just 12.5% or  $0.45 \text{ MJ/m}^3$  is basically required to keep the engine running. For an unthrottled absolute manifold pressure of 1 bar and again 60 °C mixture temperature, that would mean that the lambda value had to be 6. No spark-ignition or pilot-ignition engine can run on such lean mixtures. To restore the lambda to the ignitable range, say  $\lambda = 2.0$ , either the manifold pressure has to be reduced to around 370 mbar or the number of firing cylinders has to be skipped by about 65%. This means that 6 cylinders, running at  $\lambda$  of

about 1.9, out of a total of 18 cylinders, can easily keep the engine on its rated speed at zero load. Adding fuel gas of the same  $\lambda$  to the 12 remaining cylinders means that the fuel supply to the engine becomes tripled and that is sufficient to increase the engine power from zero load to about 30% of the rated load (compare figure 3).

With individual gas-admission valves per cylinder, also a temporary enrichment of the mixture is possible. In the lower load range, the risk of overheating and knock is much lower than for higher loads and therefore enrichment of a short duration will not cause problems. Temporarily decreasing the  $\lambda$  from 1.9 to 1.2 will add 55 % to the energy content of the mixture so that the engine has enough fuel supply to extend the initial load step to 50% of the rated load. Within a few seconds, the turbocharger will have responded to the load change so that the intake manifold pressure has increased. That will restore the air-to-fuel ratio to the desired value. This rapid temporary enrichment substantially improves the step-response capability of a gas engine.

In practice, the sensors for electric load, speed and pressure are never infinitely fast so that some additional time is required for feeding the proper signals into the controlling computer. Also, the computer always needs some time to calculate the necessary fuel gas flow with the associated settings of the gas-admission valve timing. Nevertheless, gas engines equipped with computer-controlled gas-admission valves per cylinder can easily comply with severe standards from ISO 8528.

For load steps from a starting point of e.g. 50% or 85% load, no reserve capacity is available from inactive cylinders. However, again a certain temporary enrichment is allowed. Tests have shown that loads steps of 35% at 50% load and 15% at 85% load can still be carried out within the diesel limits of class G2 of ISO 8528. That means that modern gas engines with an electronically controlled gas supply per cylinder can have an excellent upward load-step response. For downward load steps, the fuel supply to the cylinders can be rapidly cut off so that again a quick and adequate reaction is possible. Also in case of a sudden decrease in load, a short time lag occurs due to the cyclic process of a four-stroke engine. The limits in ISO 8528 are wide enough to allow the associated temporary speed increase.

### **In conclusion.**

1. Reciprocating spark-ignition or pilot-ignition engines running on gaseous fuels can have an excellent response to load changes if the engines are equipped with electronically controlled gas-admission valves per cylinder. This removes process delays while temporary mixture enrichment can be easily attained.
2. The rapid response of generating sets powered by reciprocating engines having gas injection makes them very suitable for island operation and for stabilising the grid voltage in case of weak grids.
3. Generating sets powered by engines having electronically controlled gas injection are consequently very suitable to serve as modules to build up a gas-fuelled distributed electricity supply system for developing industrial, commercial and domestic areas.
4. Full utilisation of the inherent capacities of the described gas engines is only possible with a proper understanding and tuning of the measurement and control techniques involved while a rapid electronic control system is required that ensures an engine operation within the technical limits.

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