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DISTRIBUTED ELECTRICITY GENERATION POWERED BY FUEL-INJECTED GAS ENGINES FOR MAXIMUM VOLTAGE AND FREQUENCY STABILITY IN ISLAND AND PARALLEL MODE

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Summary

Distributed generation of electricity implies the possibility of a quick implementation of new power with low capital costs and low investments in transmission systems. With modern reciprocating gas engines for driving the generators, a high conversion efficiency with low emissions is possible. Fuel-injected gas engines have such a good response to load steps that the quality and stability of the generated electricity is high. Reliability and voltage and frequency stability are very important for most electricity applications. Distributed electricity generation with suitable gas engines is therefore the preferred way to expand the local electricity supply, especially in rapidly growing economies.

Introduction

In Asia, natural gas is becoming the major fuel for supplying growing economies with energy. The clean and efficient burning characteristics of natural gas make it an ideal fuel for decentralised generation of electricity and heat. Decentralised generation implies production where it is needed and that has many advantages with respect to capital investments, the speed of power capacity build up and flexibility. Further, it offers the best opportunities for cogeneration of electricity and heat thus ensuring a maximum fuel utilisation. Optimum use of fuels is advantageous for reducing the primary energy input to a country and for limiting the emission of greenhouse gases.

Electricity is of vital importance for many production processes, for communications and for supporting modern life. The quality of electricity is closely linked with voltage and frequency stability. If the quality of the locally available electricity has to be guaranteed by a number of decentralised generators in parallel, the generating units should have an excellent response to step changes in load. Load steps occur due to changes in electricity demand and due to changes in production capacity. The international standard ISO 8528 gives limits within different classes with which generators in island mode have to comply. These standards can well be used to compare the performance of individual generating installations for distributed energy systems.

Reciprocating gas engines with fuel gas injection per cylinder can have an excellent step response. Fuel injection per cylinder supplies the gas to a cylinder right at the moment when it is needed. Temporarily enriching or leaning of the mixture entering the cylinders gives a wide-range control of the instantaneous power. Moreover, with electromagnetic gas-admission valves, the amount of fuel per injection is related to the duration of the valve opening so that exactly the amount of gas required for the instantaneous load change can be supplied. This allows a quick and safe response to changes in load. As a result, generators driven by gas engines can guarantee the power quality also in island mode. The quality of the local supply of electricity is not only guaranteed then via a better grid stability but also in case the supply from elsewhere fails. This way, ideal solutions can be found for e.g. hospitals and for industries heavily dependent on electricity supply.

This paper will explain why fuel-injected gas engines have an excellent response to load steps. The theory will be supported by test results. Also, the control strategy required for achieving the required performance will be given.

Power and speed control of engine-driven generators.

For electricity supply, the proper control of frequency and voltage is very important. Electric generators are generally equipped with a voltage control system (compare figure 1). Basically, the voltage *V* of a generator is determined by the strength of its magnetic field Φ and by its running frequency *n*:

$$V = \mathrm{c}.n.\Phi$$

In case of a very strong grid, which means that the grid has a very high capacity and a low electric resistance with a powerful supply of electricity, a relatively small generator cannot really influence the voltage of the grid. In that case, the magnetic field determines the power factor cos ϕ of the generator. In weak grids however and in island operation, the voltage of the local generator is controlling the grid voltage. In case of a strong grid, again the major power supplier determines the frequency. In island operation, the local generator is fully determining the grid frequency.

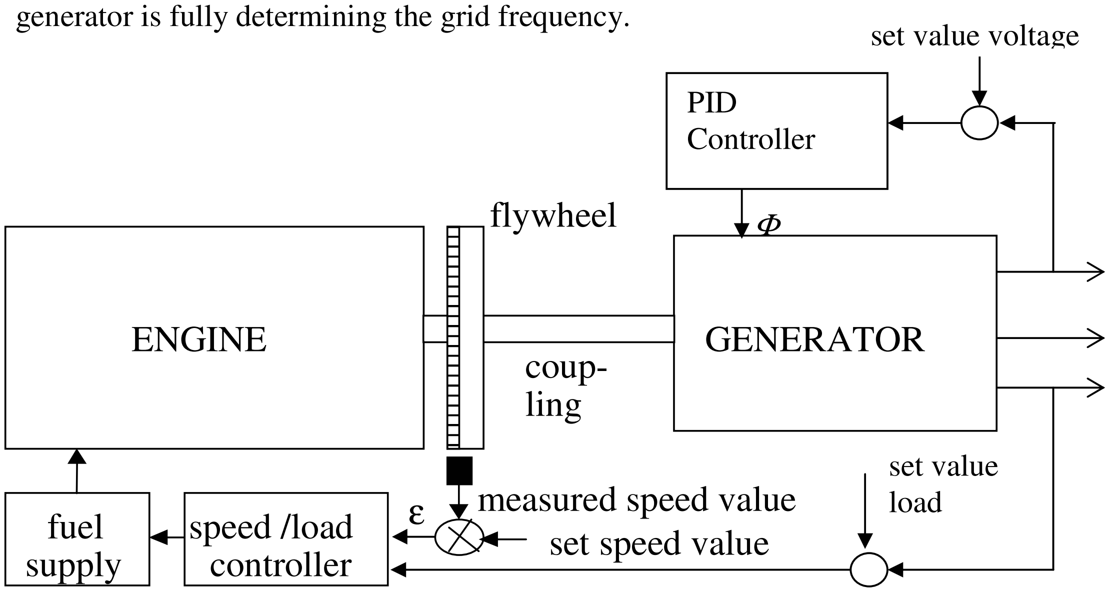

Figure 1: Voltage, frequency and load control of a generator set.

In case the engine-generator combination is running in parallel to a very strong grid, the user of the unit sets the desired load in accordance with the amount of power he wants to deliver to the grid. For this, he is using the information from the line voltage and the electric current to the grid including the power factor. There is no need to quickly adjust for small variations in generator power since the quality of the grid does not depend on that. Comparing the measured value and the set value of the power is primarily a sales tool and also a diagnostic tool: in case substantial differences or fluctuations occur, the engine-generator combination might experience some problems.

In case the generating unit is operating in island mode or in parallel to a weak grid, the generator control system has to adjust the voltage to the desired value. Any change in voltage will be accompanied by a change in load on the engine. If the fuel supply to the engine is not corrected at that moment, the engine is not able to maintain its frequency so that deviations will occur. The rotating inertia of the engine-flywheel-generator combination will temporarily supply or absorb the difference between the energy delivered by the generator and that produced by the engine. It can be shown that the initial speed change equals:

$$\mathrm{d}n/\mathrm{d}t = -\ 3600\ \Delta P/(4\ \pi^{2}\ I\ n),$$

in which: n = speed (rpm)
ΔP = load step (watt)
I = moment of inertia (kgm^2).
t = time (s).

For a running speed of 1500 rpm and a moment of inertia of 500 kgm^2, the initial speed change will be 122 rpm/s when the load step equals 1 MW. If the maximum allowed frequency variation is + or – 10%, the engine should then provide the proper torque in about a second. Otherwise, the frequency has dropped more than 10%.

The Wärtsilä control system can rapidly detect the moment and extent of such an initial speed change. The extent of the speed change is a linear measure of the change in load and therefore the control system can predict how much fuel the engine needs to satisfy the new load demand. Wärtsilä gas engines are equipped with electromagnetic gas valves to supply fuel to each individual cylinder. So, as soon as the control system detects that a different amount of fuel is required, the opening time of the valves is adapted accordingly. However, an infinitely fast response of the engine is not possible. The engine has to consume the mixture of air and gas first during the intake stroke, then compress it and finally during the power stroke the changed amount of energy released by the cylinder is supplied via the crankshaft. In a multi-cylinder engine (gas engines can have up to 20 cylinders), there is practically always at least one cylinder in the intake stroke phase. As a consequence, that cylinder can respond in about one revolution. However, the other cylinders have to follow and therefore it takes up to three revolutions before the engine is fully responding to the new fuel supply. If the speed change detection takes place during half a revolution and the fuel supply computer takes also half a revolution to calculate the new duration of the fuel supply valves, the newly required torque can be produced after roughly 4 revolutions. This equals 320 ms for a 1500 rpm engine. It will be clear that the engine speed changed somewhat during the unavoidable delay in response. In order to restore the running speed to the desired (= set) value, temporarily more power has to be produced by the engine in case of a positive load step. In case of load decrease a reduction in fuel supply will restore the running speed.

Load step capability of fuel-injected turbocharged gas engines.

Many cases exist where gas-engine-driven generators have to respond quickly to variations in load. With weak grids, the generating unit will respond to voltage changes resulting from local changes in demand. A generating set with a rapid response will help to stabilise the grid. If the grid fails, generating units running in parallel to the grid can be switched into island mode and provide the electricity for local usage. In that case, the generating unit has to control both the frequency and voltage. A number of generators running in parallel in island mode for increased reliability, which is a normal prerequisite in e.g. hospitals, failure of one generator will instantaneously increase the load of the others. In all these cases, a quick response to load changes is important.

Turbocharging is state of the art for modern gas engines. With turbocharging, the power capacity per unit of swept volume (i.e. the *bmep*: brake mean effective pressure) can be increased by more than a factor 2 compared to that of a naturally aspirated engine. That substantially increases the energy conversion efficiency (fuel costs per kWh) and lowers the specific investment costs (capital costs per kWh). With turbocharged engines that are operating with a constant air-to-fuel ratio however, the load step capacity is only quick in the load range between 0 and 30%. In that low load range, the throttle valve can fully control the mixture supply to the cylinders, al-be-it with some extra delay caused by the filling and emptying of the intake manifold. In the higher load range, the delay in turbocharger response (the so-called turbo lag) will be the determining factor for the allowed size in load steps. The approach with temporarily adjustment of the air-to-fuel ratio combined with per cylinder gas injection as applied with Wärtsilä gas engines makes turbocharged gas engines also very suitable for a rapid adjustment to load changes in the full operating range.

Wärtsilä gas engines are normally operating on an air-to-fuel ratio lambda (λ) slightly over 2. This means that more than 100% extra air is present compared to the minimum amount of air required for complete combustion. This extra air helps very much to keep the engine cool for a better efficiency, a higher reliability and lower NOx emissions. Such a lean mixture can only be ignited with prechambers using a rich mixture or with a diesel pilot. For a given swept volume of the cylinders, the volumetric energy content of the mixture inside the cylinder after the intake process determines the amount of work that that cylinder can deliver. The energy content of the mixture is directly proportional with the absolute cylinder pressure at the end of the intake stroke and inversely proportional with the absolute temperature. Within the restrictions of a given intake temperature and a given intake pressure, the lambda value can substantially affect the energy contents of the mixture. The dependence of the energy density of the mixture on the air-to-fuel ratio λ is illustrated in figure 2.

Figure 2 shows that for a given temperature and pressure, a mixture with lambda 1.0 has roughly a 90% higher energy density than a mixture of lambda 2.0. Consequently, enriching the mixture can considerably increase the power output of an engine. However,

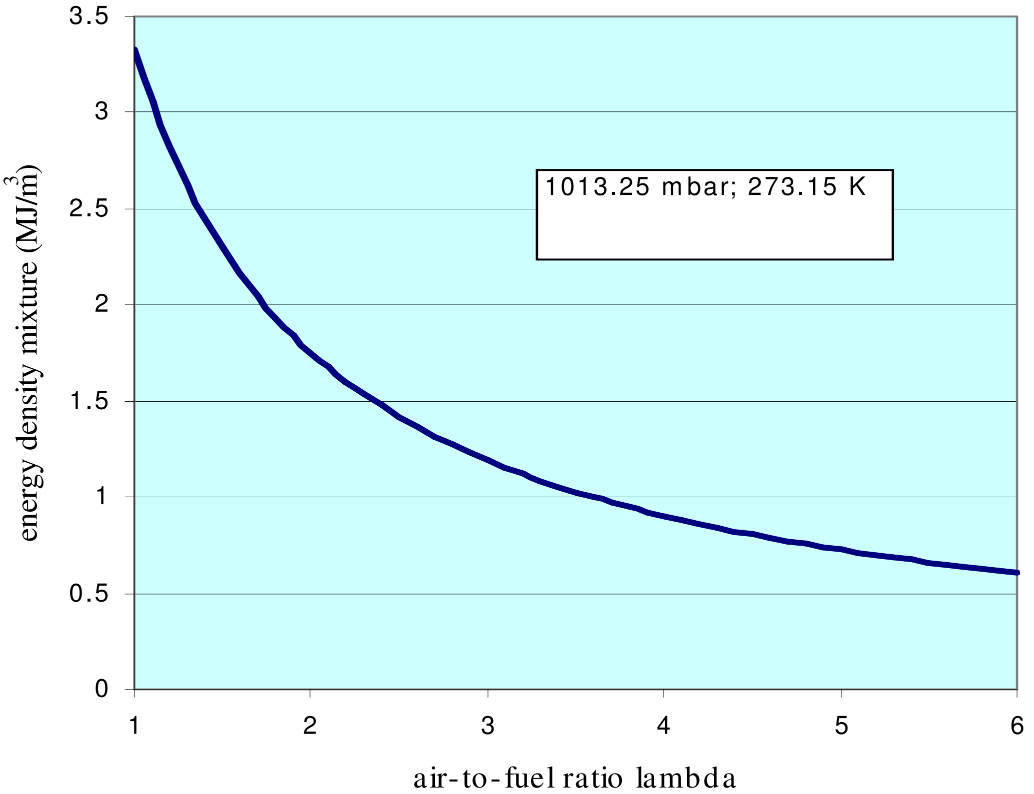

Figure 2: The dependence of the energy density of the intake mixture of the air-to-fuel ratio lambda (fuel gas: Groningen gas) at standard conditions.

the lambda value cannot just be changed to any arbitrary value. Care must be taken that the mixture will stay ignitable and that no combustion knock or engine overheating will occur. Running at mixture leaner than lambda 2.3 should be avoided since that will result in misfiring. During a substantial rapid load reduction, it is better to fully close the fuel supply to the cylinders. The Wärtsilä control system WECS in combination with fast responding electromagnetic valves with an adjustable opening time can easily be programmed to carry out the desired task. It will be clear that the step load capability is always higher at low loads than at higher loads. At higher loads, the engine will more easily exhibit knocking and the work per cycle can also more easily reach overload. With a proper limiting of the fuel gas supply depending upon the instantaneous operating conditions, the lambda-control method offers an excellent step response performance.

Figure 3 gives an example of an attainable positive load step capability depending on the starting point. The graph is an interpolation of actual measurement results. From zero load, the load step can be 50%; naturally, this value decreases drastically when the starting load is approaching 100%. In practice, the capability depends on external conditions such as atmospheric pressure, ambient temperature and gas quality. The load-step performance is very close to that of modern diesel engines. This means that natural-gas-fuelled reciprocating engines are very suitable in providing a stable frequency and voltage.

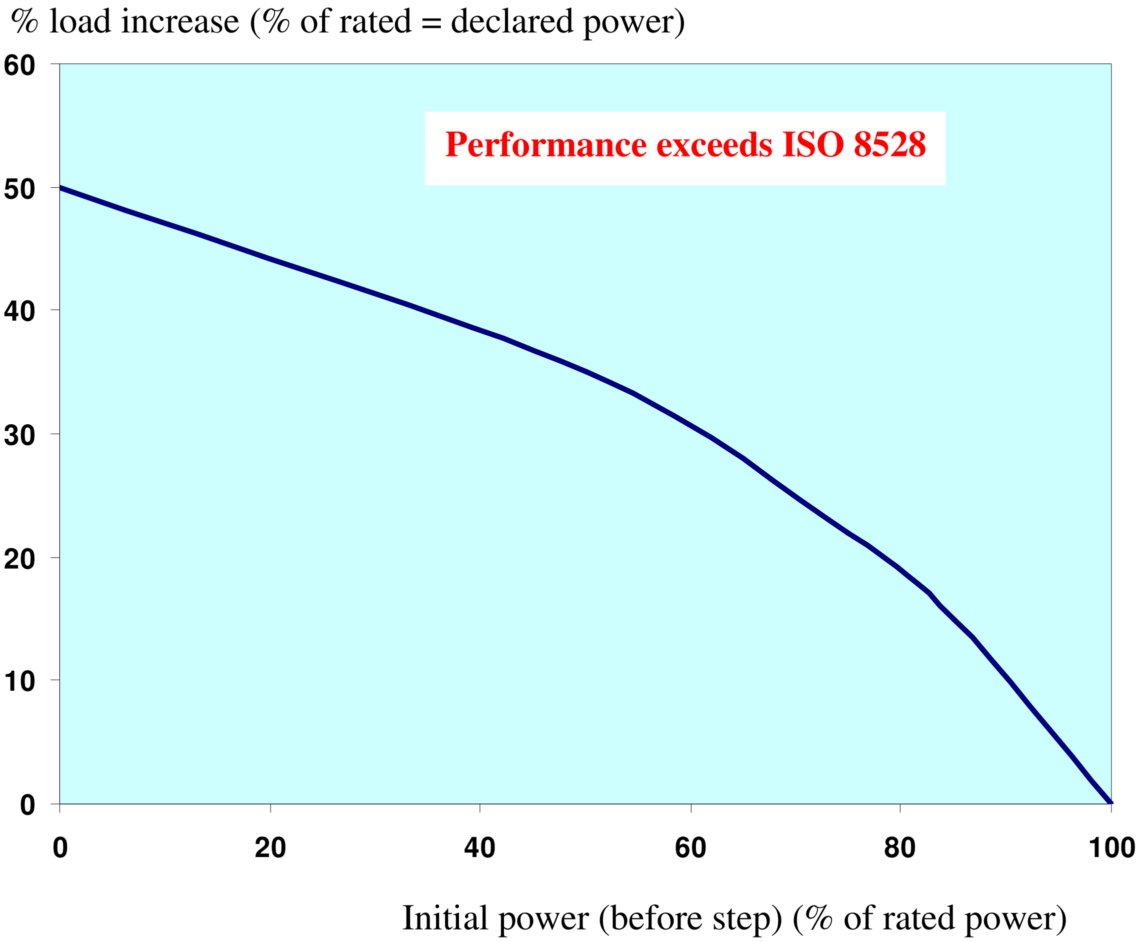

Figure 4: Example of possible load step capability of a fuel-injected reciprocating gas engine.

Summarising conclusions

1. For a rapid expansion of local electric power capacity, generators driven by reciprocating gas engines offer a good option. They combine a short lead time with a high conversion efficiency, low emissions and flexibility in power capacity.
2. The excellent response of fuel-injected gas engines to load steps makes them very suitable for island operation and for stabilising weak electricity grids.
3. With a proper tuning, fuel injected gas engines can easily comply with ISO 8528 for island-mode performance.