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TRANSIENT RESPONSE BEHAVIOUR OF GAS ENGINES

1 Introduction

Recent emission regulations and the trend towards utilization of waste gases and renewable fuels have generated a rising interest in using gas engines in applications where Diesel/HFO engines were commonly used. Since various types of gas engines with distinct advantages and shortcomings are available in the market, there is an uncertainty about the suitability of these engines for applications with a demand for fast transient response behaviour.

This paper explains general physical and thermodynamic properties of the most common industrial gas engine types. We point out what should be observed when using these engines for stationary or maritime applications. Automotive applications are not covered in this paper.

2 Transient response requirements (Stationary application)

2.1 Island operation

In Island operation one or several gensets feed power into a local grid. Since the genset’s load step capability is restricted, a strategy for switching the various loads onto the grid is required. Any load change must be followed by the respective change in power generation. The genset must be able to pick up this load without being stalled. Moreover, voltage and frequency are expected to stay within defined limits. It is common to start with the largest consumers since most gensets can pick up higher load steps at low base loads.

If several gensets are operated in parallel, the local grid should be able to bear with the shutdown of one engine. This leads to a considerable load step for the remaining gensets at an already higher base load.

2.2 Grid parallel operation

Although most engines in grid parallel operation run at constant power, fast adaptation to power demands can provide additional benefit. This way, the genset may assist in reducing the peak loads of a facility (“peak shaving”) or lower the facility load from the grid during peak hours with high electric rates. Finally, the decentralization of the energy market and the growing share of weather-dependent wind and solar energy create an increasing demand for fast-reacting and well-controlled sources of electrical energy to compensate for peak loads or drops in power generation. Consequently, this leads to fluctuating feed-in tariffs. Gensets being able to power-up within short time will take advantage of this.

As an extra benefit, gensets continuously running in grid parallel operation may take over the internal load in case of an external grid failure. This transition from parallel operation to island operation results in a certain load step for the gensets at high base load.

2.3 Mechanical drives

The most common applications where industrial gas engines are used as direct mechanical drives are reciprocating or rotating gas or air compressors and water or hydraulic pumps. Transient response requirements depend on the application and include load steps due to clutching or opening of media valves as well as power-up procedures with load ramps. Unlike genset applications compressors and pumps are often operated at variable or load-dependent speed.

3 Transient response requirements (Maritime application)

Auxiliary engines

The requirements on auxiliary gensets supplying electrical power for cargo cooling, air conditioning, ventilation, stabilizers, water treatment, etc. are basically the same as in stationary island operation.

Propulsion

During maneuvering the main engine must follow quickly the load demands. At most vessels, fast response is most important at lower loads. At hard weather, engines are exposed to considerable varying load due to rolling or windmilling. Finally, on plants with declutchable propellers the engine must take a load step when clutching in.

Engines directly coupled to fixed pitch propellers (FPP) are operated along their nominal propeller curve where engine load and power are a function of the engine’s rotational speed whereas engines coupled to controllable pitch propellers (CPP) operate in a much larger range of load vs. speed. This must be taken into account during engine layout and dimensioning.

In case of electric propulsion, the supplying gensets are usually operated at constant speed. The propulsion motors are driven by frequency converters (variable frequency drives, VFD). When discussing transient response requirements for the engines, the VFD’s control behaviour must be considered.

Shaft alternators

Propeller shaft alternators offer additional flexibility: In Power take-off (PTO) mode the main engine feeds electrical power to the auxiliary load while in Power take-in (PTI) mode auxiliary gensets support the main engine by boosting additional electrical power to the propeller.

4 Two-step model of transient response behaviour

4.1 Load step acceptance

The transient response behaviour of an internal combustion engine is most commonly described by its ability to cope with a sudden increase of load. We use the following two-step model for turbocharged combustion engines (gas or diesel) to explain the behaviour of different engine types:

Step 1 Load acceptance: The engine’s speed governor increases the engine power almost instantaneously by adding more fuel.

Step 2 Recovery time: Subsequently, the engine needs a certain time to speed up the turbocharger and to reach a new stable operation point. After this, the engine is ready for the next load step.

4.2 Varying load

Often, the load profile of an engine is not a sequence of well-defined load steps, but rather a continuously varying load. Fast and limited load variations require immediate load acceptance (step-1 is critical). For slower and larger load variations such as power-up in parallel mode step-2 is more dominant.

5 Transient response behaviour of gas engines

5.1 Direct injection Gas engines (Gas-Diesel engines)

Unlike the commonly used gas engines with OTTO combustion, direct injection gas engines inject the fuel gas at high pressure directly into the combustion chamber at ignition time. Thus, they use the DIESEL combustion process. Since there is no risk of knocking combustion, the transient response behaviour of these engines is basically the same as the behaviour of Diesel engines with liquid fuel.

5.2 Port injection Gas engines

Step 1: More fuel at constant air flow

On Port injection Gas engines power is increased in step 1 by injecting additional fuel gas while the amount of combustion air remains the same. Thus, the engine runs temporarily with a rich gas-air mixture until the turbocharger is able to deliver the required air flow (step 2). In principle, the same takes place in a Diesel engine, but due to the different combustion process the load acceptance is subject to specific limitations.

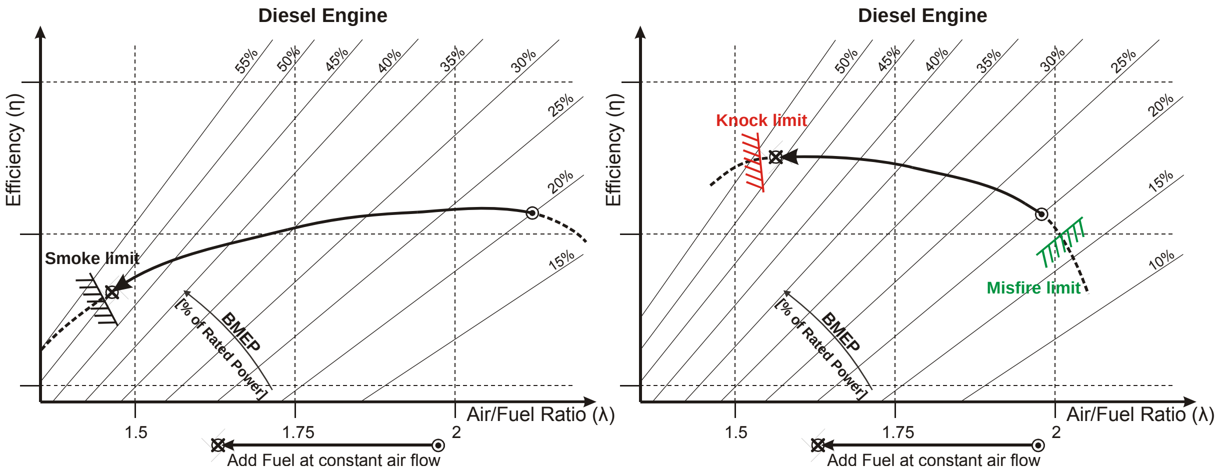

Figure 1: Illustration of Step 1 – Injecting additional fuel at constant air flow (Low base load of 20% rated BMEP)

Figure 1 shows the efficiency of Diesel and Otto combustion processes when adding fuel at constant air mass flow at low base load. The Diesel combustion has a wide operating range; the amount of additional fuel is restricted by the smoke limit. The Lambda range of the Otto combustion process is much smaller being limited by misfiring on the lean side and by knocking combustion on the rich side.

On the other hand, the efficiency of the Diesel combustion drops at lower air/fuel ratios whereas the efficiency of the Otto process increases. So, the load acceptance capabilities of Diesel engines and Port injection Gas engines are similar at low base loads.

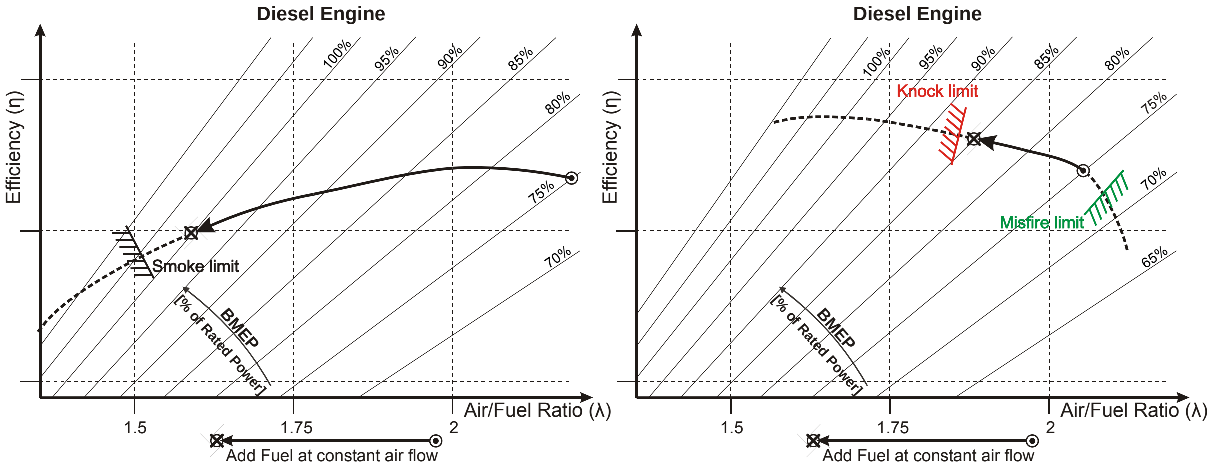

Figure 2: Illustration of Step 1 – Injecting additional fuel at constant air flow (High base load of 75% rated BMEP)

Figure 2 shows the same for higher BMEP close to the rated power of the engine. Here, the knock limit strongly delimits the amount of fuel gas that can be added. This is the main reason why the Gas engine can take smaller load steps at higher loads.

Furthermore, the diesel engine can be overboosted with high excess air allowing for larger amounts of fuel to be injected at the load step. The gas engine has very limited overboost capabilities due to misfiring at lean mixtures, i.e. at high air/fuel ratios.

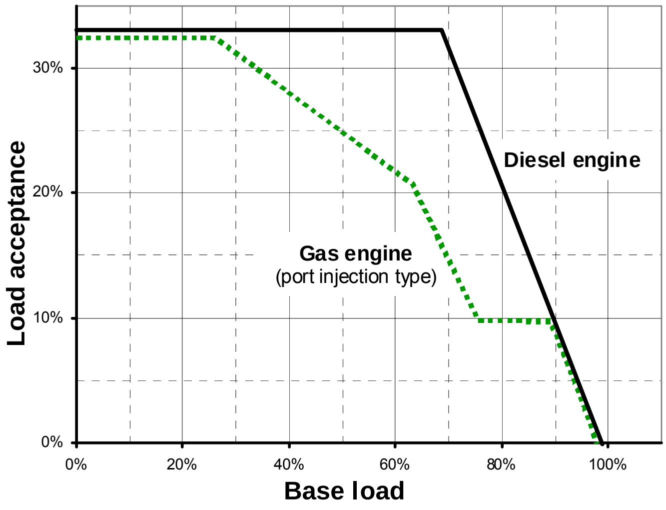

Figure 3: Maximum load acceptance (Example)

Figure 3 exemplifies the maximum load acceptance of a large bore port injection Gas engine for maritime application. Typically it is significantly lower at higher base loads.

5.3 Mixture-charged Gas engines

Typically, mixture-charged Gas engines use a throttle to control speed or power. Opening the throttle increases the *amount* of gas-air mixture in the cylinders while the air/fuel *ratio* is controlled independently.

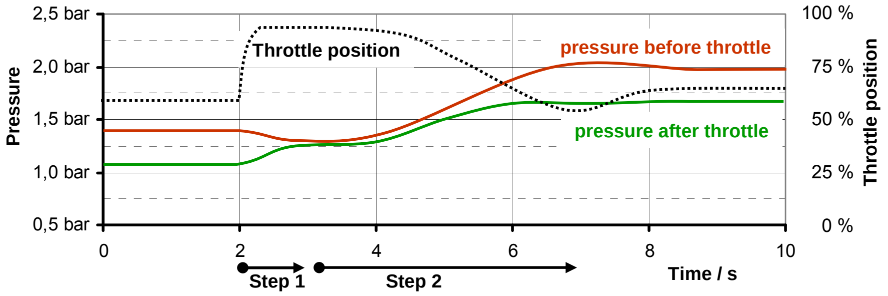

Figure 4: Course of boost pressures after a load step (mixture-charged Gas engine)

In Step 1 the speed governor opens the throttle, the boost pressure after the throttle and thus the engine power rise. After the recovery time (Step 2) a stable pressure difference over the throttle, the throttle reserve, has been built up again and the engine is ready for the next load step.

The recent progress in gas engine technology yielded cutting-edge engines in terms of low emissions (NO_X) and high efficiency (low CO_2 footprint). These engines are optimized for continuous operation at full power in parallel mode, typically in CHP applications. They run at high BMEP reducing the engine's specific fuel consumption. In order to keep NO_X emissions low and to prevent knocking combustion, lean mixtures and Miller valve timings are used which, in turn, requires high boost pressures. For that reason large high efficiency turbochargers are applied to this type of engines. For efficiency reasons, the throttle reserve is kept as low as possible. The trade-off of these engines is a considerably lower load acceptance due to lean mixtures, knock limitations and the large turbochargers which need more time to speed up after a load step.

On the other hand there is a class of engines designed for robust operation and best transient behaviour at the cost of higher emissions and lower efficiency. In general, these engines are also more tolerant to ambient conditions and fuel gas properties. They run at lower BMEP thus reducing the risk of knocking combustion. Operated at richer mixtures, they require only moderate boost pressures so that smaller turbochargers, typically one for each cylinder bank, are applicable. A larger throttle reserve and the rich mixture improve the engine's load step capabilities in step 1, fast accelerating turbochargers reduce the recovery time in step 2.

Figure 5 shows the load step response during island operation of two typical gas engines compared to a standby diesel engine. Even Low BMEP mixture-charged Gas engines show significantly longer recovery times than a standby Diesel engine. The difference in load acceptance between the two Gas engines is obvious; the big load step even overburdens the High-efficiency CHP Gas engine.

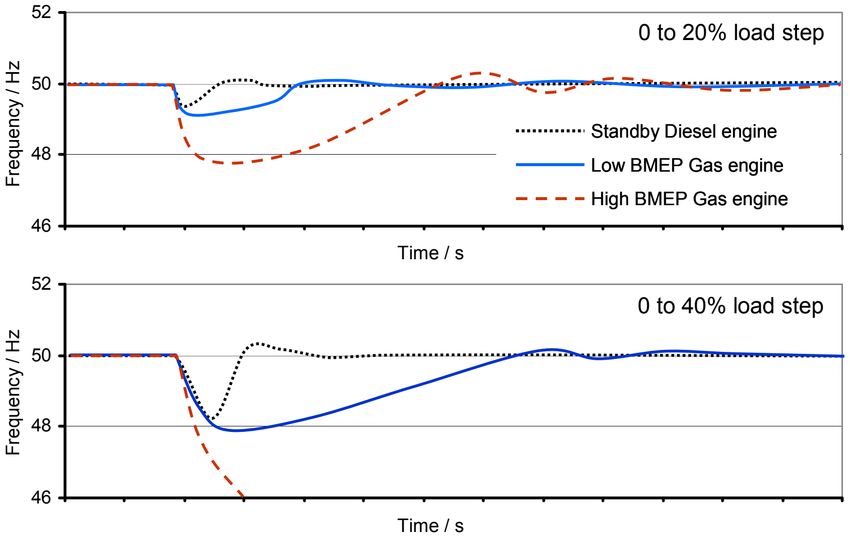

Figure 5: Load step response example of typical Standby Diesel and Mixture-charged Gas engines

6 Ambient conditions

Gas engines, and in particular the lean burn types, are generally more sensitive to ambient conditions compared to diesel engines. Any given performance data of an engine refers to the specified ambient conditions. If the site ambient conditions deviate from these, not only engine efficiency and emissions will be affected, but also its transient response capabilities.

Higher air inlet temperatures and higher altitudes result in lower air density. At higher loads an appropriate turbocharger matching with an increased boost rate can partially compensate for this. At zero load operation the turbocharger is not yet operating due to lack of exhaust energy. Hence, high air inlet temperatures and high altitudes definitively reduce the engine's ability to pick up the *first* load step. Inlet temperatures lower than specified may bring the turbocharger into surging, especially during load rejections. Clogging of the air filter causes pressure losses before the turbocharger compressor and effects engine performance in the same manner as engine operation at high altitudes.

High receiver or manifold temperatures due to insufficient charge air cooling also reduce the air mass flow to the cylinders. In addition, the knock margin is negatively affected so that the enrichment of the gas-air mixtures in step 1 is further limited.

Finally, recovery times and power-up times of a cold engine may be significantly longer due to lower exhaust energy for speeding up the turbocharger.

See also our Working Group's Position paper "About the influence of ambient conditions on performance of gas engines".

7 Influence of Gas quality

In contrast to well standardized Diesel fuels, gas engines are faced with a wide range of possible fuel gas types and qualities. The properties of the fuel gas affect the load acceptance in two ways:

- Low calorific fuel gases (e.g. biogases) limit the maximum achievable energy content in the cylinder. This is most relevant at lower loads where the engine can be operated with rich mixtures.
- Gases with low Methane Numbers (MN) show a lower resistance to knocking combustion. This considerably limits the injection of fuel gas at higher loads (see Figure 2).

8 CIMAC Position on transient response of gas engines

There are various types of Otto Gas engines with characteristic properties and advantages, but none of them can serve as a 1-by-1 replacement of a diesel engine. At lower base loads, the load acceptance of port injection gas engines may be comparable to those of diesel engines, though with higher BMEPs the load acceptance is increasingly restricted by knock limitations. Mixture charged gas engines are available in different versions, each of those being optimized for certain applications.

The ISO 8528-5 on Generating Sets defines four genset performance classes G1 to G4. Due to their specific limitations most gas engines will be classified in class G4 where the requirements are defined by an Agreement between Manufacturer and Customer (AMC). This individual agreement should be made on the basis of a thorough specification of the engine and its environment.

Any gas engine specification must include a definition of the fuel gas and the expected variations of gas composition and Methane Number. Ambient conditions such as altitude, intake air temperature and charge air cooler temperature must be specified as well.

The load step requirements should include all consumer characteristics (load types, soft-starts, etc.) and maximum admissible frequency and voltage deviations. Load management must be designed such that large load steps at high base loads are avoided and the replacement of a failed genset is considered.

Gas engines are also suitable for ship propulsion if transient response is most important at low power maneuvering as in most vessels. If electric propulsion systems or shaft alternators are incorporated, the complete grid and the load management on the vessel should be considered for classification.

Special attention has to be paid to proper LNG gas management. See also our Working Group's Position paper “Information about the use of LNG as engine fuel”.

Conclusion

Thorough specification of transient response requirements is the key to the use of gas engines in applications where diesel engines have been traditionally employed. The advantages are low exhaust emissions, higher efficiency, reduced carbon footprint and potentially the use of alternative fuels. Clever load management can further mitigate transient loads and allow for the application of higher efficiency gas engine types.