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Power Generation Stability and Response in DP Applications – An Overview of Modern Diesel Engine Performance

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Introduction

Diesel engines are the preferred prime movers for power generation on DP vessels, predominantly because of their reliability as prime movers and their ability to respond to changing power needs.

Most modern DP vessels use diesel-electric propulsion with diesel driven generators and motor driven propellers or thrusters. These applications typically use multiple (three to eight) gensets feeding AC power to a common electrical network.
There are various methods and levels of sophistication applied to the way the electric power is shared between parallel generators and divided to different consumers.

This paper looks briefly at the fundamentals of the two commonly used load sharing methods; *isochronous* and *speed droop* control, from a power system performance point of view.
Reflections are made regarding integration of diesel engine controls with overlaying Power Management System (PMS) and Vessel Management System (VMS).

The paper continues with an overview on modern diesel engine performance and identifies certain key functionalities and design aspects that are essential to optimum diesel engine performance.

The paper concludes with some reflections on particular load sharing schemes that serves practical for the operators when trying to run the gensets as close to optimum as possible.

Frequency Control and Load Sharing

With frequency control, we define the task of maintaining a specified frequency (or frequency range). In practice this is done by controlling the diesel engine rpm by the use of a speed governor.
Traditionally, mechanical/hydraulical governors were used (and are still in use today). The governor is driven mechanically by the engine crankshaft (through a gear drive) and uses a speed droop control method, where the engine rpm is 3-4% lower at 100% load compared to unloaded condition.
Load sharing is simply achieved by having similar speed droop settings on all gensets.

In modern applications, electronic speed control units (often referred to as electronic governors) are commonly used.
The engine speed is measured by means of pickups, which typically sense the gear teeth on the engine flywheel. Normally there are two pickups for redundancy. An actuator translates the output signal from the control unit to mechanical fuel rack movements.
The use of electronic controls opens up possibilities such as isochronous load sharing, multiple control settings and useful features such as adjustable and automatic loading ramps, filtering of oscillations etc.

With the introduction of more sophisticated engine fuel systems, such as common rail fuel injection, electronic speed control is a given. In fact, the trend for marine diesel engines is to have the speed governor functions built in the engine's "blackbox" control unit, in a similar fashion as in modern automotive diesels. In addition to the fuel quantity also fuel pressure and injection timing can be adjusted according to the current operating condition.

Interaction Between Speed Control and External Systems

In a diesel electric DP application, speed control is only a primary function. From a system performance point of view, much more essential is load sharing between different generators connected to the busbar.

First, it is essential to define certain terminology.
I would like to distinguish between *Load Sharing* and *Load balancing*.

Load sharing is the function performed strictly by the speed governor, either using droop mode or isochronous mode. The external systems (power management system, etc.) cannot actively affect the instant load sharing between the generators. Load sharing is active, real time based on the governor dynamics.

A power management system can, in the case of speed droop mode operation perform load balancing and frequency correction (to compensate for the speed droop), by adjusting the speed reference of the governor(s). Adjusting only one genset's settings will affect both load balance and bus frequency. Adjusting all units' speed reference simultaneously will correct the frequency of the system.
The time span of frequency corrections is normally several minutes. In no case should frequency corrections occur more frequently than 30 seconds between each increase or decrease command. The PMS should ideally adjust the load balance only when a generator is recently connected, or before disconnecting a generator. The PMS should determine the length of the increase/decrease pulse based on the size of the desired correction and then wait for 30 seconds or more before performing a new correction. In particular when performing small corrections. Too fast corrections from the PMS can cause unnecessary fluctuations in load and frequency, which in worst case never dampen out.

In case of isochronous load sharing, everything is controlled internally and between the governors. The load is normally shared symmetrically, unless it is intentionally biased.

Diesel Engine Performance

Varying environmental conditions (wind, wave, current) will cause varying power needs of a DP application. In addition to the strictly position keeping (thruster) loads, other loads on the vessel may be highly cyclical, such as drilling drawworks, cranes, pipe tensioners, etc.

A varying power need requires the diesel generator sets to be as responsive as possible.
Transient performance of diesel engines is limited by certain physics such as inertia and flow dynamics.
Analyzing areas of importance for good transient response identifies certain functions and details of a diesel engine that directly influence loading performance.

Turbocharging
The turbocharging system is certainly the most important factor in a modern diesel engine. In quest of higher power outputs and better fuel economy, the turbocharging pressures have increased tremendously since the 1970's. This has increased the thermal efficiency and lowered the fuel consumption.
With a higher degree of turbocharging, engine transient response has developed in a negative direction. In the 1970s, it was not uncommon that engines could be loaded from idling to full power in a single step load. Today, with highly efficient (supercharged) engines, maximum loading increments of 25…33% is not uncommon.

The ever increasing focus on reducing exhaust emissions, primarily Nitrogen oxides (NOx), has brought about "green" valve timing configurations (e.g. earlier inlet valve closing, so called Miller timing) in combination with higher supercharging pressures.

Regardless of the supercharging degree, there are certain fundamentals with how the turbocharging system is designed.
The turbocharger converts the energy in the exhaust gas flow to rotational movement of the turbocharger rotor. The better the flow pulses from the different cylinders can be gathered (with less losses), the better engine response.

The design and layout of the exhaust header, between the cylinders and the turbocharger(s) affects loading performance significantly. A so-called pulse charging systems can more effectively gather the kinetic energy in the exhaust gas compared to so-called constant pressure systems.

The pulse charging systems group 2 or 3 cylinders to one exhaust header. The grouping is depends on the number of cylinders. Engines with cylinders in multiple of 3 (6, 9, 12, 18-cylinder) can utilize the very efficient 3-pulse charging system. Engines with cylinders in multiples of 2 (4, 8, 16-cylinder) can use a 2-pulse system. In practice 2-pulse charging is only used on 4-cylinder and in some cases also on 8-cylinder engines due to the large number of pipes. The pulse charging principle is still utilized also on 8- and 16-cylinder engines, but in a slightly modified form called Pulse Converter system. Every group of two cylinders has a separate pipe all the way to the turbocharger, but two groups are joined together just before the turbocharger.

Routing all exhaust pulses into one large exhaust manifold forms a so-called constant pressure exhaust system. This system can be tuned for very high efficiency at a fairly narrow load band and is hence often used in base load type of applications, but is less suitable for applications with varying power requirements and a need for rapid loading response. The larger volume in the exhaust manifold, the larger time constant. The response of a single pipe exhaust system can be improved by reducing the volume, but interference between the cylinders and efficiency losses limit how much the volume can be reduced.

What is the latest in turbocharger development then? Variable geometry turbochargers have started to appear on the market. With variable nozzle ring geometry, the turbocharger operating envelope and performance can be changed during operation to optimize the engine performance for certain conditions. This type of turbochargers is useful e.g. in lean burn gas engines, where combustion is sensitive to gas quality and air temperature variations.
Adjustments are relatively slow and VTG turbocharging is not a practical tool to optimize loading performance with. The operating conditions of a turbocharger on a heavy fuel engine are rather demanding and VTG technology is at least today not ready for heavy fuel engines.

Common Rail Fuel injection

Common Rail fuel injection has made its entry in the marine engine market. Instead of the conventional one "monoblock" injection pump per cylinder, the CR system uses a common pressurized header or "rail" which feeds all cylinders with fuel. The rail pressure is maintained with one or a few pumps. The injection valves are electronically controlled and inject a suitable amount of fuel depending on engine speed and load. The benefit with the CR fuel injection is the possibility to use a high fuel injection pressure over the entire load range. With conventional fuel injection systems, injection pressure is lower at lower loads, resulting in less efficient combustion.

Although CR has not been developed specifically to improve loading performance, experience has shown that CR fuel injection makes the engine more responsive. In addition to the constant fuel injection pressure, CR opens up the possibility for advanced fuel mapping, such as variable injection timing, pre-injection, rate shaping, etc. CR can also be used to compensate for unfavorable ignition properties of the fuel (mainly for heavy fuel applications).

BMEP

Brake Mean Effective Pressure is a parameter to keep an eye on if loading response is a top priority.
BMEP is an indicator often used to determine how highly rated the engine is. BMEP also, in a way, indicates how advanced the engine design is ("how far pushing it"). Clearly the trend has been an increase in BMEP (ref. also increase in turbocharging). In the mid 80's BMEP was usually in the 20-22 bar bracket. Today 27 bar is not outrageous (aggressive but not "far out"). The 20 bar BMEP diesel engine from 1985 was probably capable of loading in two steps 0-50-100%. A modern 27 bar engine will struggle with 3 steps and prefer 4 steps.

a-value

The a-value expresses the maximum acceleration. It is thus related to both power output (more correctly torque) and total mass moment of inertia.
Inertia is both a friend and a foe in rapid load changes. In a sudden load increase, high inertia helps prevent a high frequency drop, but high inertia also increases the time required to return to nominal speed.

For ideal genset loading performance it is crucial to match the diesel engine, flywheel, coupling and generator rotor, forming a system or rotating masses. The system's a-number defines the acceleration (and deceleration) properties and is a key parameter designers use to optimize transient response.
Dynamic simulations are useful in determining optimum system inertia for both sudden load increase and sudden load decrease scenarios.

Can Loading Performance be Improved Using Special "Gadgets"?

Most marine diesel engines are designed to meet the needs of very wide markets; from earthmoving machinery to various kinds of marine vessels. In a way you could say that everything is a compromise.
The question whether additional "gadgets" could be useful to improve loading performance is from that perspective not illogical at all.
A method used already for a number of years, with varying success, is air injection into the turbocharger.
The principle is to reduce the lag time of the turbocharger when applying a big load step (increase). Air nozzles directed at the turbocharger rotor are used to accelerate the turbocharger and hence reduce the lag. So far the system is simple and practical.
The challenge is how to control the system. Most systems are triggered by engine speed (i.e. frequency dip). This is in most cases too late. The "damage is already done". More advanced systems uses load feedback from a large consumer of feed forward signals from other control systems.
Air consumption is another challenge with this technology. If load changes are frequent, the air consumption is high and require large air vessels and compressors to cater for the demand. Jet assist also put additional stress on the compressor wheel of the turbocharger, which in the case of an aluminum compressor wheel can shorten the lifetime considerably.
For frequently changing load levels, such as often seen in drilling operations, air injection has proven fairly unpractical. The lagging response may in worst case cause larger speed variations.

When a load step occurs, until the turbocharger accelerates, the diesel engine suffers from air deficit. It is then natural to look at ways of catering for the air demand to the combustion until the turbocharger is accelerated and "in charge".
Two stroke diesels use mechanical air blowers to ensure sufficient gas exchange at low loads. This is a must for the 2-stroke process. The same principal is sometimes used on 4-stroke engines to reduce smoke formation at lower loads, i.e. to increase the air/fuel ratio.

The method has some merit but may be unpractical as a means to improve transient response on higher loads due to the high air mass flows and pressures.

A more direct way of avoiding combustion air deficit is to force the rotation of the turbocharger, even in conditions where the exhaust gas flow is not able to maintain turbocharger speed. Such a concept involves either an electric motor or a power turbine on the turbocharger rotor shaft.
This concept was used already in the 1960's in icebreakers, preventing the engines from stalling when operating in sever ice conditions.
Using electrical high speed motors would maybe offer the most convenient control interface, but represents a fairly challenging mechanical interface due to the high rotational speed of the turbocharger. Magnetic bearings would be a must.

On the controls side of things, there are numerous innovative approaches that can be put to work in improving diesel genset loading response. Feed forward control is maybe the approach that first comes to mind.
For certain applications, using a load feed forward signal, may be very useful, especially if the load changes fall in an established pattern. In most cases the measured generator load is not so useful. It would be necessary to start compensating just before the load change. Any feed forward control requires careful tuning, especially if soft flexible couplings must be used to control torsional vibrations.

Today's diesel engines (without CR) use actuators that translate the speed control unit output signal into a mechanical movement of the fuel rack. These actuators are normally hydraulic. Electric actuators have entered the market and represent potential for faster response in the actuating portion of the system (but the mechanical levers and link rods remain).

Load Sharing – Symmetric vs. Asymmetric
In normal operation, symmetric load sharing fulfils most operational demands. There may however be scenarios where asymmetric load sharing is preferred. The reasons may be for example problems with a component in either unit (e.g. such that it can not be operated above a certain load) or simply that one of the units has been overhauled and a running in program is recommended.

Arranging for asymmetric load sharing is a straightforward and simple task for a modern power management system. It is valuable for the operators in trying to run the power generation system as close to optimum as possible.

Conclusion

Modern diesel engines are more efficient, more optimized than in the past. They are also optimized in a more narrow band and face constraints due to e.g. emissions requirements, making them less tolerant of large load changes.

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Additional systems and features may improve loading response, but hardly any of the available technologies have been commercialized as selectable options from the engine builders.

New technologies such as common rail fuel injection and load pulsing control marks potential for future improvements in diesel engine loading performance.