COMPARISON OF ELECTRIC POWER AND PROPULSION PLANTS FOR LNG CARRIERS WITH DIFFERENT PROPULSION SYSTEMS

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ABSTRACT

Dual-Fuel Electric Propulsion has become the preferred solutions for LNG carrier newbuildings in the range from 140 000 cbm to 200 000 cbm. The experience from the first vessel delivered is very good with respect to the performance of the electric propulsion system. In the last two years only a few were ordered with traditional steam turbine propulsion system, and two-stroke propulsion with reliquefaction is so far only selected for LNG carriers with more than 210 000 cbm capacity. A fourth alternative with Gas Turbines has also been considered but yet not ordered for LNGC. All these different propulsion systems require a HV power plant, either to supply only the cargo handling plant and/or reliquefaction plant or combined with electric propulsion. For steam turbine propulsion vessels the utilization of this power plant is relative low as the cargo pumps are only operated at the discharging terminal. The two stroke propulsion system requires an even bigger power plant because of the reliquefaction compressors of 5–6 MW. The utilization of this power plant is slightly higher than for steam turbine, but also for this alternative the HV power system is only fully utilized at the discharging terminal. Further the starting methods are discussed for the reliquefaction compressors, but the use of frequency converter is the only solution to ensure a stable and reliable power plant.

Dual-fuel Electric Propulsion LNG Carriers vessels are ordered in France, and last year also in Korea and Japan. These vessels combine the high voltage power system for both cargo handling and propulsion; hence the total installed power is less than for any other type of propulsion. Frequency converters are also natural part of electric propulsion systems, and the power systems for these two alternative propulsion systems are similar, also with respect to design and engineering practice. In an electric power system of this size and complexity, special consideration must be made to essential characteristics as short circuit levels, harmonic distortion, transient conditions, starting of large consumers etc.

Recorded performance of the electric propulsion system shows the possibilities to operate the propulsion motors in constant power, which gives stable operation of the power plant operating in gas mode, even at rough sea conditions. Also the crash stop performance is superior to other propulsion systems because of the ability to stop and reverse the propeller in less than 30 seconds.

INTRODUCTION

Electric power systems on todays LNGs consist of relative large and modern High Voltage (HV) power plants with frequency converters for control of propulsion and gas compressors. This gives some new requirements and opportunities for operation and maintenance that differs from previous generation of LNG Carriers.

Traditionally from the 1960s the LNG carriers have been equipped with conventional steam turbine propulsion plant together with a Low Voltage (LV) electric network for supply of cargo pumps and other electric consumers. As the vessels have been growing in size, the installed electric power increased consequentially, mainly because of the need for more cargo pump capacity. When the vessel size passed 130 000 cbm the total installed electric power requirements normally increased above 10MW, and leading to a very high short circuit rating of the LV electric network, HV system was introduced in the first LNG carriers in 2000. 6,6kV or 3,3kV systems were installed with HV cargo pumps and compressors for the cargo handling, however still with steam turbine propulsion.

In 2003 with the introduction of alternatives means for utilizing the boil-off gas in engines, the first Dual Fuel Electric Propulsion (DFEP) LNG carriers were ordered in France [1] by Gaz de France. Figure 1 shows the first DFEP LNG carrier put into service (“Provalys”).

The main driving factor for the change of propulsion system was the overall improved efficiency, but also other factors as less total installed power, lower emissions, improved maneuverability, etc should be emphasized [2]. Basically the same HV power plant as used for the conventional LNGs is installed on these vessels, except for the additional

Figure 1. Provalys, DFEP LNG Carrier

equipment of variable speed drive system for the propulsion, and upgrade of installed generator power to match the propulsion requirement. Other propulsion systems as two-stroke direct driven diesel engine with reliquefaction plant was also ordered in 2004 for LNG carriers above 210 000 cbm. These vessels also require a large installed HV power plant for the cargo handling and reliquefaction plant. As the reliquefaction plant requires gas compressors up to 6MW, converter solutions are necessary, in order to start and operate the reliquefaction compressor motors.

Further alternative propulsion systems are also under discussion such as Gas Turbine Electric Propulsion. This system will utilize Gas Turbines for prime movers, however the electric distribution and propulsion system will be same as for the Dual-Fuel electric propulsion system.

In the future, one can foresee that more stringent requirements will be introduced to LNG carriers, such as operation in ice, high maneuverability, dynamic positioning (LNG RV) etc. Such requirements will lead to further development of LNG carriers and the propulsion arrangement. One possibility is to use podded propulsion, which have been successfully implemented in other ship types such as cruise vessels, icebreakers, offshore supply vessels and ice going tankers. Figure 2 shows schematically the development of electric power and propulsion system for LNG carriers.

This paper describes the different configurations of the electric power system for the various propulsion systems, and special characteristics and requirements for the electric power distribution and propulsion systems are discussed. Further the power plant utilization is compared, and different starting methods of reliquefaction compressors are discussed. Finally the performance of the electric propulsion system is presented.

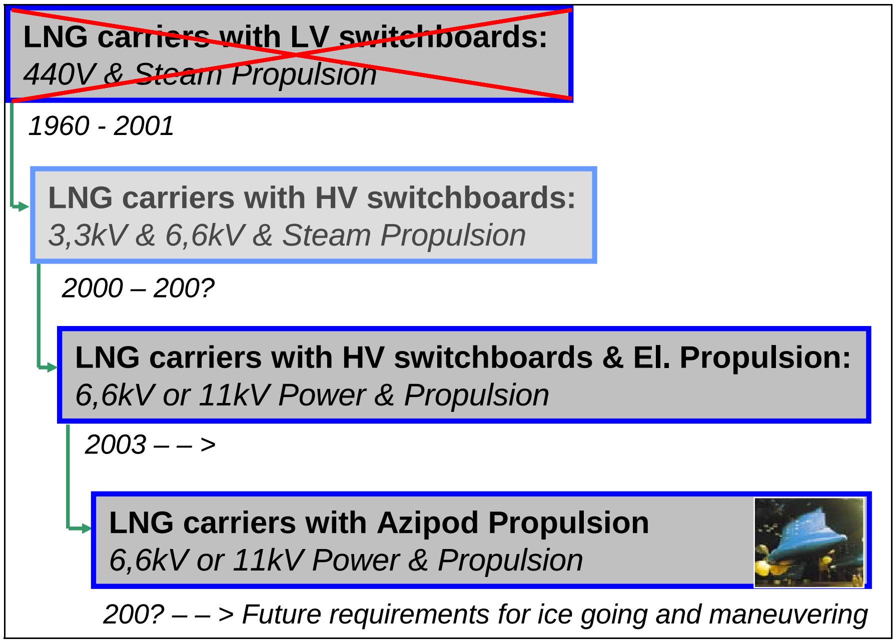


Figure 2. LNG Carriers; towards a new generation

POWER SYSTEM CONFIGURATIONS

The different electrical power system configurations are described in the following subsections. All the various systems have a High Voltage power plant, and except for steam turbine propulsion all propulsion systems have frequency converters for controlling either propulsion or reliquefaction compressors. This means that attention must be paid to short-circuit level, transient conditions, and harmonic distortion for all the various systems [3].

Steam Turbine Propulsion

After 2001, almost all new buildings of steam- turbine LNG carriers have been equipped with HV power generation and distribution system of either 3,3kV or 6,6kV. As the installed power has increased to more than 10MW, the short circuit level of the main switchboard will require a higher voltage level than the traditional LV-systems. Figure 3 shows a typical electric power plant configuration of a steam turbine propulsion system. Two steam turbine generators and one diesel generator brings the total installed power to a level between 10-12 MW. Most of the LNG carriers the HV switchboard is split into 4 sections, i.e. two main switchboards and two cargo switchboard. All HV cargo pumps, Low Duty (LD) and High Duty (HD) compressors are normally installed on the cargo switchboard, and the ballast pumps and bow thrusters are normally installed on the main switchboard.

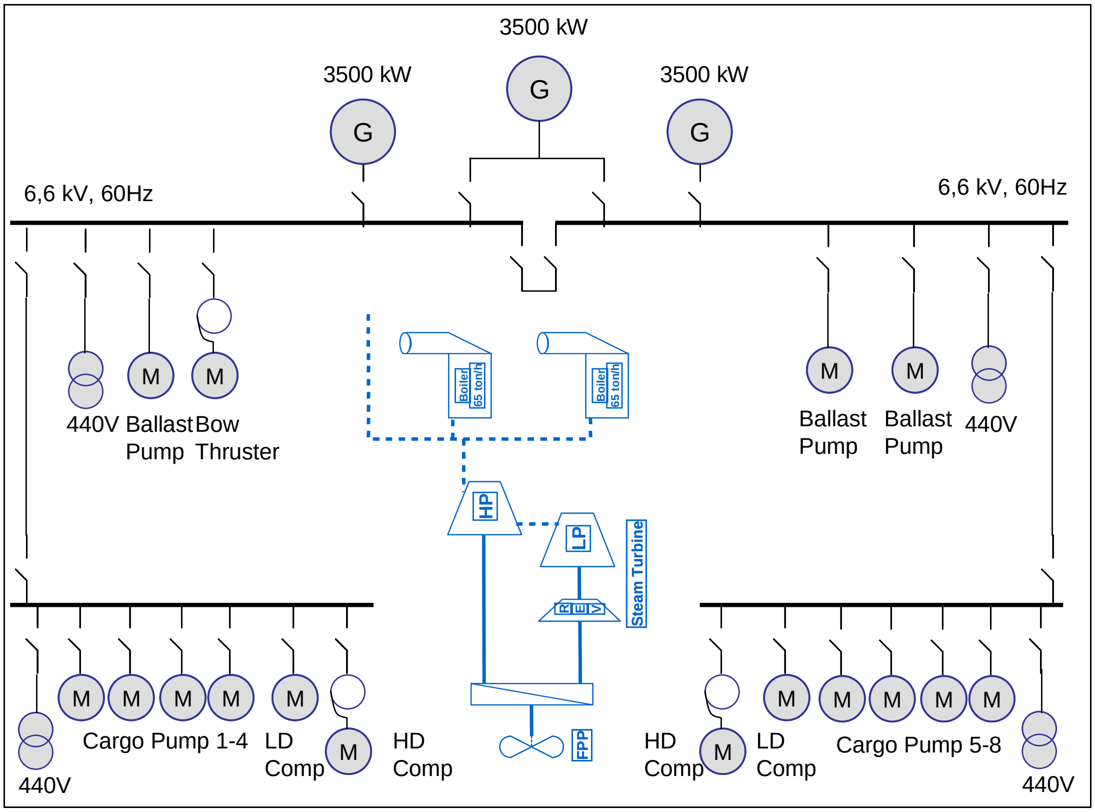


Figure 3. Steam turbine propulsion system

Dual-Fuel Electric Propulsion

With the introduction of Dual Fuel (DF) engines Electric propulsion became highly attractive for LNG carriers, especially since the total propulsion efficiency increased with about 40% compared to the steam turbine system. The emissions will also be lower due to the increased efficiency, and the possibility to operate 100% on gas [4].Other advantages for the electrical system are considerably less total installed power onboard the ship, since the electric power plant will serve both the propulsion system and cargo handling system.

Figure 4 shows a typical configuration for a DF power and propulsion system. The main power generation and distribution system is similar as on the Steam Turbine ship types. The rating of the generators is adjusted to match the required propulsion power, but for the ship sizes around 150 000cbm it is still feasible to use 6,6kV switchboards. If the ship size increase to 200 000 cbm or above, 11kV switchboard systems should be considered as the required propulsion power would be higher and consequentially also the installed generator capacity. However at present state the cargo pumps are only available up to 6,6kV, which means that step-down distribution transformers between the main and cargo switchboard will be necessary.

The additional equipment compared to steam turbine system is the variable speed electric drive systems for the propulsion. The configuration in Figure 4 shows an example with single propeller and two electric motors connected to a common gearbox, and each motor is RPM controlled by a frequency converter.

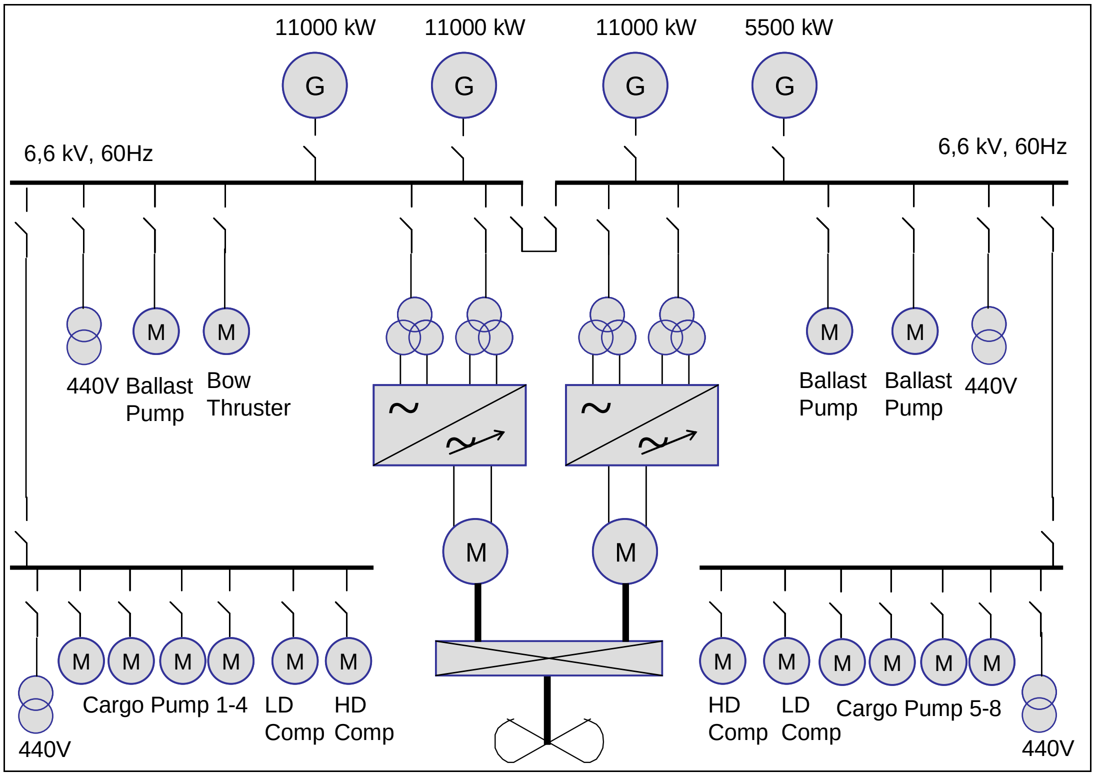


Figure 4. Dual-fuel electric propulsion configuration

Other configurations as twin propellers (with or without gearbox), single propeller with two motors in tandem connection (without gearbox) are also applicable for LNG vessels. The electric network will be the same for all configuration. It should be noted that electric propulsion system is not a new concept, it has existed for a long time on other ship types as for example cruise ships. The experience from these ship types are brought into the design of the electric propulsion plants for LNG carriers.

Two-Stroke Propulsion

Two stroke propulsion has so far been the selection for ultra large LNG Carriers, i.e. more than 210 000cbm. The propulsion system consists of twin propellers with two-stroke engine directly on each propeller shaft. This system requires a relative large reliquefaction plant (5-6MW) onboard for converting boil of gas back to liquid form for return to the cargo tanks. Even though the propulsion efficiency for the two stroke machine itself is high, the total overall system efficiency is lower than for DF electric propulsion, as the running of the reliquefaction plant will require additional 5 – 6 MW of electric power. Together with the cargo pumps, this will require an electric power plant with 15-20MW of installed power in addition to the two stroke propulsion plant. Figure 5 shows a typical configuration of the power plant for two-stroke propulsion solution. The main distribution- and generation system is similar to the other systems with a 4 split main HV switchboard and 4 generators. Compared with the DF electric propulsion system the only difference is that the propulsion drives are replaced with drives for the reliquefaction compressor plant (one duty and one standby).

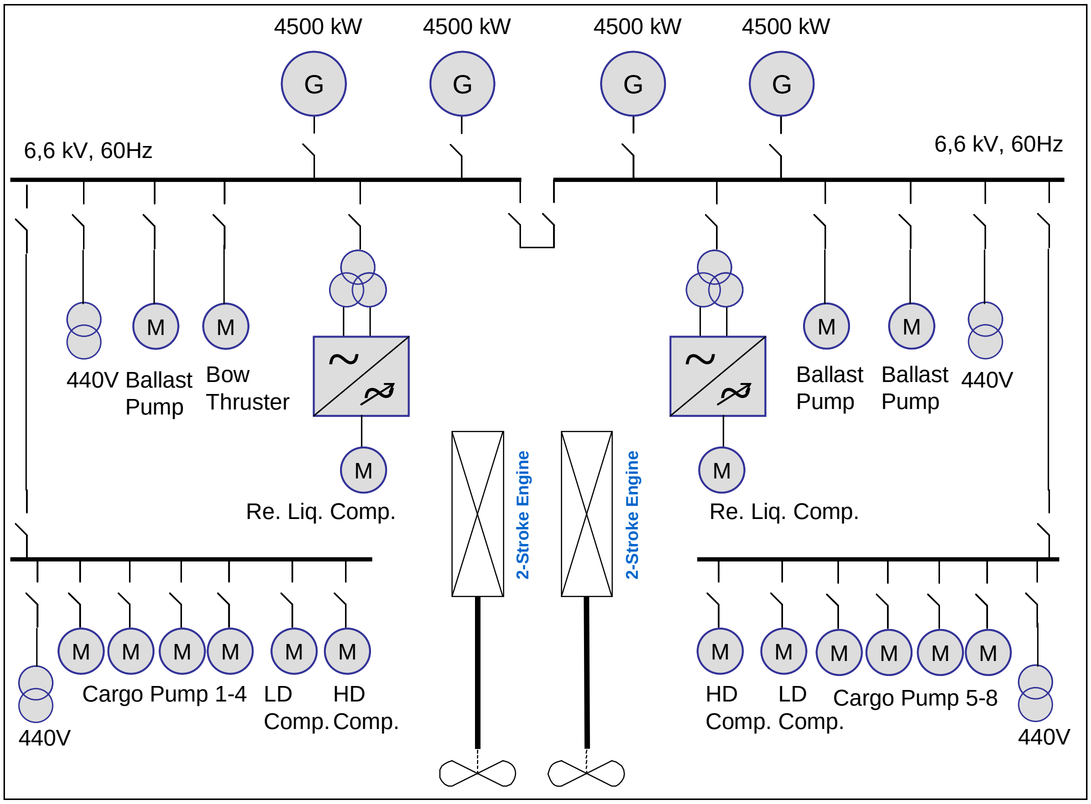


Figure 5. Two-stroke engine propulsion configuration

Gas Turbine Electric Propulsion

Another alternative for LNG carrier propulsion system is to use gas turbines in combination with electric propulsion. The efficiency of this solution would be in the same range or even higher than for the dual fuel electric propulsion, depending if combined cycle is used or not. The following two different solutions are considered; 2 gas turbines in simple cycle or 1 larger gas turbine in combination with 1 steam turbine in combined cycle. For both solutions one or two additional diesel generators are also considered. Besides the high efficiency (combined cycle), easy installation and maintenance are highlighted as the main benefits [5].

Figure 6 shows an example of a typical layout (combined cycle) with one big main gas turbine generator, one smaller steam turbine and one back-up diesel generator. 11kV is suggested as voltage level for this system, since the propulsion arrangement is for vessels above 200 000 cbm. 11kV also reduce the current rating for the circuit breaker of the gas turbine generator to a reasonable level. The electric propulsion system is identical to the propulsion system presented for the DF alternative, except for the twin propeller solution which is also normally proposed for LNG carriers above 200 000 cbm. The propulsion power for these vessels would typically be in the range from 2 x 15 - 17MW. The twin propulsion system may also utilize one gearbox (single input, single output) on each shaft in order to minimize the size and the cost of the electric propulsion motors.

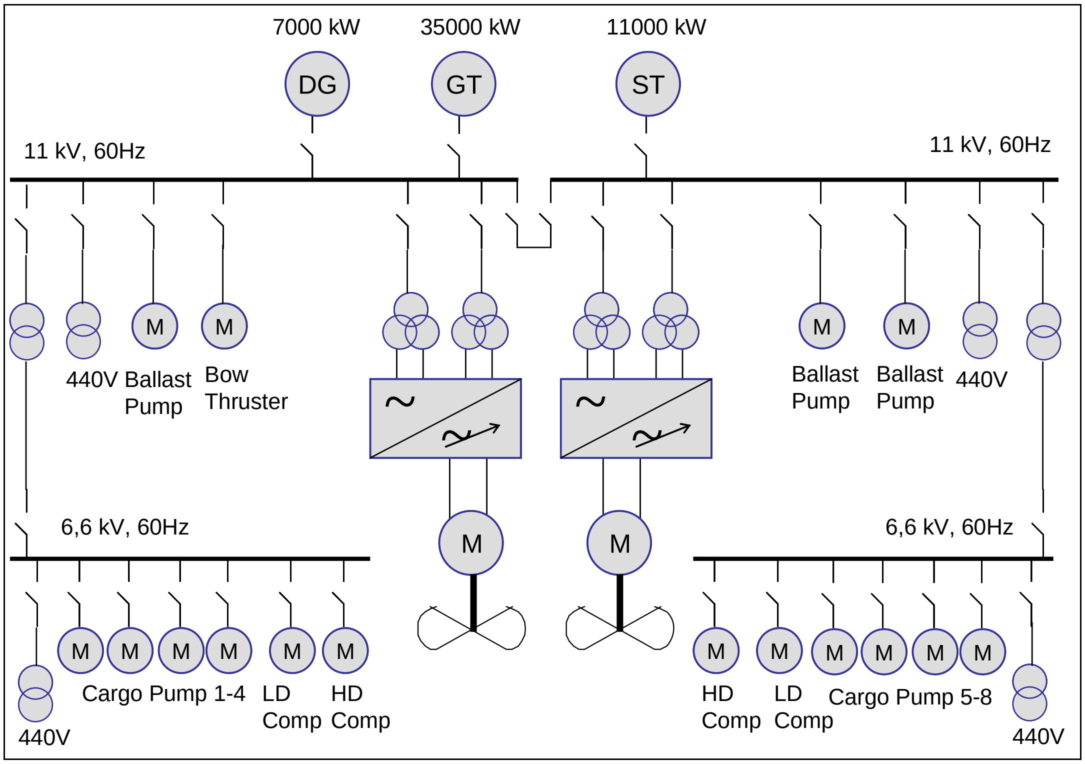


Figure 6. Gas turbine electric propulsion configuration

COMPARISON OF ELECTRICAL CHARACTERISTICS

Power System Utilization

The different alternative propulsion systems for LNGCs have different electrical load demand, but one common requirement is the need for a High Voltage power plant. This means that the switchboard distribution system will be almost identical for all the various system, but the usage of this system will be different from case to case. With electric propulsion the dimensioning criteria for the electrical power plant is the required propulsion load, while for the other systems the dimensioning criteria is the cargo pump capacity together with the auxiliary load and reliquefaction load (when used). The different alternatives are compared in the following sub-sections, and summarized in Table 1.

Table 1. Comparison of electric power plant utilization:

Propulsion type	**Steam (140K)**	**Dual-Fuel (150K)**	**Two-stroke (220K)**	**Gas Turbines**
Total Efficiency (including el. losses)	29%	42%	40%*	45%**
Installed el. power	10-15 MW	30-40 MW	15-20 MW	45-55 MW
Min. voltage level	3,3 kV	6,6 kV	6,6 kV	11 kV
Utilization (seagoing)	15-20 %	80%	35-45%	70-80%
Utilization (unloading)	70-80 %	25%	50-80%	25%
Total installed power (propulsion + aux)***	45 MW	38 MW	56 MW	50 MW

* Including reliquefaction power of 5W and assumed propulsion power of 30MW.
** Combined cycle.
*** Typical values

Dual Fuel Electric Propulsion:

The propulsion power for vessel size around 150 000cbm will be in the range of 2 x 13MW, and auxiliary load about 2 MW. Including the electrical losses in the propulsion drive chain, the electrical load will be about 30MW from the switchboard. With a typical installed generator capacity of about 38 MW, approximate 80% of the installed power will be used during sea going, which is the most time consuming activity in the total operation profile of the vessel. The same power plant can be used for both propulsion and cargo handling, which gives the lowest total installed power among the different alternatives. It should be noted that there are different philosophies with respect to installed generator capacity. Some ship-owners require 100% propulsion power, even with one generator/engine out of operation, while other ship-owners accept a reduced propulsion power in this situation. This means that the total installed generator power will vary from case to case.

Steam Turbine Propulsion:

This alternative has separated the propulsion system (steam turbine) and the cargo handling system (electrical power plant). As the power plant is dimensioned by the capacity of the cargo handling system this will not be fully utilized during seagoing. Typical installed power of a 140 000 cbm vessel is about 11 MW, and the required electrical load in seagoing is less than 2 MW, which means that less than 20% of the power plant is utilized during sea-going.

Two-Stroke Propulsion with Reliquefaction:

This solution has also separated the propulsion system and cargo handling system, and in addition there is a reliquefaction plant installed to take care of the boil-of gas. As there might be a need to operate the reliquefaction together with the cargo pumps the electrical power plant should be increased, and a typical installed power plant is about 18MW for a 220 000cbm LNG. The reliquefaction plant consumes about 6MW at full load and together with auxiliary load of approx. 2MW max 45% of the installed power is utilized during sea-going.

Gas-Turbine propulsion:

For Gas Turbine Electric Propulsion, as for DFEP, it is the propulsion power that is dimensioning for the power plant. However, the proposed solutions so far has been to use commercially available turbines which have been most suitable for a propulsion power corresponding to a vessel size around 250000 cbm. This alternative has also normally been proposed with a standby diesel engione of 5-10MW in addition to the gas turbine system. This leads to a total installed power of approximate 50 MW. The propulsion power for this vessel size would be about 35MW. Together with an auxiliary load of approx 3MW this means a power plant use of about 75% in sea-going condition.

Starting of Large Consumers

In all marine power systems the main loading on the distribution system consist of electric motors used for various pumps and compressors. During start of an electric motor the starting current can be as high as 5-7 times the nominal current. The power system must therefore be dimensioned to tolerate this additional loading during starting sequence. For small motors this is normally not an issue, however for larger motors this must be carefully checked in the design stage that the power system can tolerate the start sequence or if reduced voltage starting methods may be considered. For LNG carriers the following motors should be checked against the installed power:

- Bow thruster.
- High-duty compressor.
- Reliquefaction compressor (when installed).

The following starting methods are available:

- Direct On-Line (DOL): No additional equipment is required, rated starting current of 5 to 7 times nominal.

- Auto transformer start (ATR): Additional transformer is needed to feed the motor at a reduced voltage during startup.

- Soft starter (SST): Additional soft starter with varying voltage supply to the motor.

Bow Thruster and High Duty Compressor

The bow thruster and high duty compressor can normally be started DOL for electric propulsion vessels as the installed generator capacity is sufficient to comply with the transient voltage requirements, with a condition that more than one generator may be connected online during the starting period. However for steam turbine propulsion and two stroke propulsion the installed generator capacity is not sufficient, and ATR starting of these motors are mandatory.

Reliquefaction Compressor

For the reliquefaction compressor motor (which is in the range of 5-6MW), the only safe starting and operating method is to use a frequency converter. This is the only solution that can 100% guarantee a safe start-up without exceeding the classification limits for voltage transients and black-out of the power system during startup. The frequency converter operates with the principle of controlling both the voltage and the frequency to the motor. This gives the possibilities of applying a high start torque without a large starting current. If there is a shutdown or stop from the compressor side, the frequency converter can give a controlled shutdown with respect to motor speed and current in order to minimize the transient effects on the power system.

Other starting methods have also been evaluated based on following conditions:

- Starting of a reliquefaction compressor of 5,4 MW at a power plant consisting of 4 x 4,3MVA generators.
- Evaluation is based on the requirement of successful start with only 3 generators connected.

Soft-Starter:

By using a soft starter for starting, the voltage will gradually increase until the current limit. The ramping must be slow enough in order for the AVR to follow without giving a transient voltage dip. However the min. current limit must be big enough to ensure enough torque to start the motor. With the given starting torque requirements from the compressor the minimum current limit is about 5 x rated current. This will be applied during the whole starting sequence, and give an over-current at about 230% of the generators during the start-up time. The generators have to be constructed with extremely low reactance's and with a bigger excitation machine in order to keep the voltage within classification limits. However at the end of the starting period there will be an over-voltage that exceeds the classification limit.

Auto-transformer:

By using an auto transformer, the starting current is reduced by the selected tapping of the transformer. The lower limit of the possible tapping is given by the required torque curve of the compressor for the whole starting period. With the given compressor torque the minimum tapping to guarantee a safe start is 85%. The starting current from the network is then reduced by a factor of 0,852. For a motor with 6 x In (Nominal Current) at start this means the network starting current is about 4,3 x In. Assuming a rated motor current of 521A this gives 2240A network current which is 200% of rated generator current (3 x 377A). For a tapping of 70% (however this may not be sufficient to overcome the starting torque) the starting current from the network is 2,9 x In. Assuming a rated motor current of 521A this gives 1531A network current which is 135% of rated generator current (3 x 377A). Special design of generators with extremely low reactance's and excitation units is needed to give a transient voltage drop within the classification limits. However for both tapping suggestions there is a high risk of blackout and serious damage to equipment if the motor trip during the starting period, because of over-voltage. Also after startup the motor is directly coupled to the network and it is not possible to give a controlled shutdown in case of trip or failure of the compressor plant.

Harmonic Distortion

In all ship power applications with frequency converters, harmonic distortion will appear. This has to be checked and calculated in the design stage, and proper measures must be taken before installation. Harmonic distortion is a phenomena caused by non-linear loads consuming current components from the power station with frequencies different from the nominal frequency. These current components will cause distortion of the main voltage which again may disturb sensitive equipment. The harmonic distortion level is normally denoted by the use of THD index, and the level is expressed in %THD. The classification rules have normally stated limits for how much distortion is allowed, and in practice if the THD is less than 5% on the main switchboard voltage, harmonic distortion should not cause any problem on the distribution system and normal equipment.

For steam-turbine propulsion harmonic distortion has not been an issue because the HV power system mainly consists of rotating machinery without the use of frequency converters. However for all the other propulsion alternatives this issue must be considered as the large loads as propulsion or reliquefaction needs frequency converters for control or start-up purpose.

In electric propulsion the main load is the propulsion plant with variable speed drives for rotating the propellers. Because the voltage level of the main switchboard does not correspond to the voltage level of the converters, propulsion transformers are needed to supply the frequency converters with a suitable voltage. This gives also benefits for the harmonic distortion level, as the different transformers can be constructed with individual phase-shifts of the windings. Combining different transformers together with different phase shifts, harmonic components will be suppressed or cancelled out within the drive system, and not influence the main switchboard. The system of such transformers is often referred to as 12-pulse, 24-pulse, 48-pulse etc. systems. The higher pulse numbers the lower harmonic distortion. However for each step higher in pulse number, more transformers are needed. To create a 24-pulse system two 3-winding transformers are needed. For converter types with diode-bridge rectifiers (Voltage Source Inverters), 24-pulse system is more than sufficient to get the harmonic distortion level below 5%. Figure 7 shows an example of harmonic distortion on the main 6,6kV switchboard voltage for a typical Dual Fuel Electric Propulsion LNG carrier at 100% propulsion load.

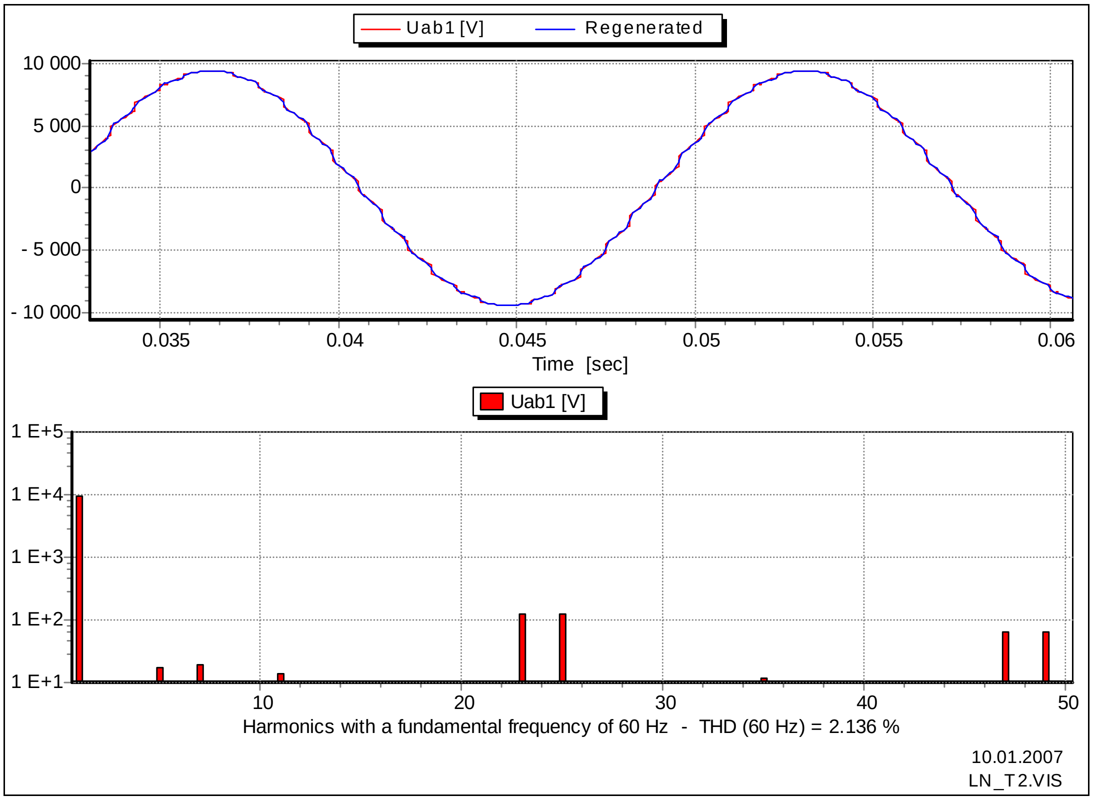


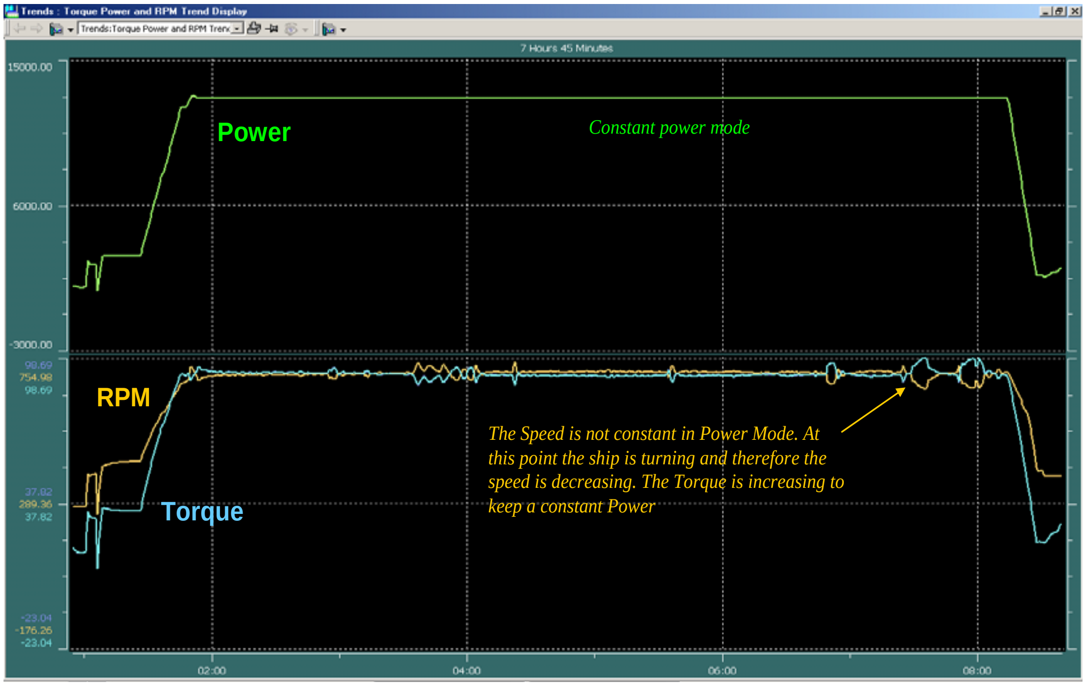
Figure 7. Harmonic distortion example; Main HV SWBD voltage; 24-pulse and 100% propulsion power

For two-stroke propulsion the reliquefaction compressor drives will due its size normally be of 12-pulse design. This means that the harmonic distortion may exceed 5%, if the power plant is not carefully designed. The parameters of all the components as generators, transformers, and converters will influence the harmonic distortion level.

LNG ELECTRIC PROPULSION PERFORMANCE AND EXPERIENCE

The first large size (154K) LNG carrier with electric propulsion is now in operation, and the performance of the electric drive system has been according to the specifications and expectations. Electric propulsion system is not a new technology; it has been used for cruise liners and ice-breakers for more than 20 years. However the use of dual-fuel engines was a new concept and operating the engines in gas-modes gives some additional requirements to the propulsion system compared to the other ship types with electric propulsion. Operation in gas-mode gives a higher sensitivity to the electric load variations compared to normal diesel engine operation on HFO or MDO. With the applied propulsion concept as described in the previous sections (synchronous propulsion motors and voltage source inverters with DTC control [6]), there are two different operation principles available:

- Constant RPM mode: The propeller RPM is controlled to a constant value given by the lever reference from the bridge.
- Constant Power mode: The propeller power is controlled to a constant value given by the lever reference from the bridge.

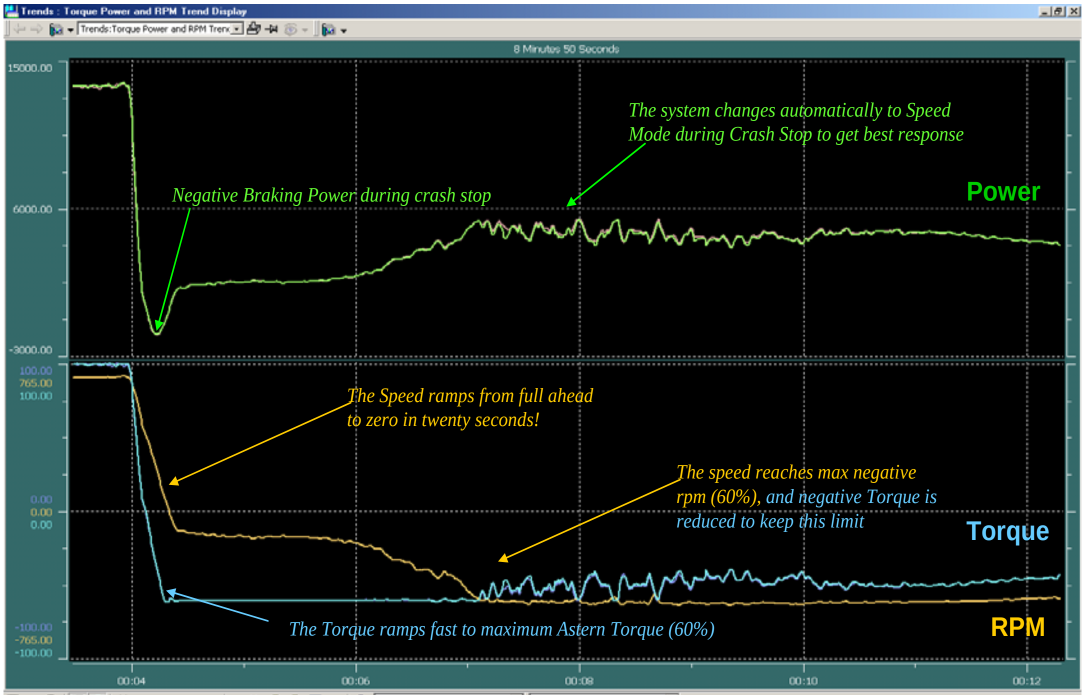


The Speed is not constant in Power Mode. At this point the ship is turning and therefore the speed is decreasing. The Torque is increasing to keep a constant Power

Figure 8. Propulsion motor power, RPM and torque at 100% propulsion power

In constant RPM mode the power on the propeller, and hence also the electric power to the network, will face fluctuations dependent on the weather situation and/or ship turning. If such fluctuations are too big there is a risk that the dual fuel engines will change from gas mode to diesel mode. In constant Power mode the propulsion drive system will be able to give a constant load to the electrical network and ensure a stable operation of the DF engines in gas mode. This is achieved by the fast DTC control of the converter, with a torque response time in less than 3 ms. In this mode the RPM will be allowed to fluctuate according to the propeller loading condition. Figure 8 shows the power, torque and RPM of one propulsion motor during endurance test of one LNG carrier at 100% load. As shown in this figure the electric power consumed by the propulsion drive system is constant.

Another interesting feature of electric propulsion is the crash stop sequence. During a crash stop sequence the drive system will respond to the bridge lever command (change from full ahead to full astern) by first stopping the propeller, and then reverse the RPM to maximum allowable negative RPM. During the stopping sequence the propulsion motor will operate as an electric brake for a short time, hence feeding power from the propeller to the converter. This reverse power is consumed in a separate braking resistor. This feature means that the propeller can be stopped quite fast, and from the test presented in Figure 9, it can be seen that the propeller was stopped within 20s. The ship was stopped within 7 minutes.



The system changes automatically to Speed Mode during Crash Stop to get best response

Negative Braking Power during crash stop

The Speed ramps from full ahead to zero in twenty seconds!

The speed reaches max negative rpm (60%), and negative Torque is reduced to keep this limit

The Torque ramps fast to maximum Astern Torque (60%)

Figure 9. Propulsion motor power, RPM and torque at Crash Stop Test.

CONCLUDING REMARKS

The different propulsion solutions available for LNG carriers have been presented from the electrical power system point of view. All the different solutions require a High Voltage (3,3kV, 6,6kV or 11kV) power system as the installed electrical power is more than 10MW for all the systems. For steam and two-stroke propulsion the HV electric power plant is only needed for supplying the cargo pumps and the reliquefaction compressors. This means that this power plant is only fully utilized at the unloading terminal. For electric propulsion vessels (powered by Dual-Fuel Engine or Gas Turbines) the electric power plant is dimensioned according to the propulsion requirement from sea-going conditions. The same power plant can then be used also for the cargo handling, hence minimizing the investment cost for propulsion and auxiliary machinery. Of all the alternatives, electric propulsion has the lowest total installed power, and the highest utilization of the installed electrical power plant.

Of the four alternative propulsion systems presented, Dual-Fuel electric and Two-stroke propulsion with reliquefaction have been selected for most of the LNGC new-buildings ordered the last two years. Both of these solutions require a relative large power plant which also includes frequency converters for either running the propeller (Dual-Fuel) or the reliquefaction compressors (Two-Stroke). For the two-stroke engine propulsion alternative, the staring method of the reliquefaction compressors has been addressed. Because the rating of these motors is too large for Direct On-Line (DOL) start, various methods with reduced voltage starting were analyzed. The only starting method to guarantee a safe with all conditions within class requirements is to use a frequency converter. This means that the power system of these two alternatives must be designed and engineered as a system and not component by component. The parameters of all the main components as generators, switchboards, transformers and motors will all influence the total performance of the power system, and if not carefully system design is done there is a risk of poor performance of the power system.

The performance of the electric propulsion system has been presented for one DFEP LNG in operation. The electric propulsion system with the use of frequency converters with Direct Torque Control (DTC) has proven to fulfill and exceed the expectations and specification requirements. In particular the system has proven excellent performance in sea-mode condition with operation in constant power mode, and crash stop situation.

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