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Fuel-efficient power plant featuring variable speed generation system for DP drilling units

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ABB AS

Abstract

Variable speed power generation can be achieved in several ways, and this article will discuss and present new solutions that can be applied for DP class drilling units. For other smaller types of offshore DP vessels DC distribution technologies already exist, as for example the ABBs Onboard DC Grid concept, enabling variable generator speed operation. The main motivation for this is the fuel saving potential that lies within the possibility to run diesel engines in a fuel-optimal condition even at lower load by reducing the speed.
Further, two methods for applying variable speed generation will be presented and discussed:
- LV DC grid system for mid water vessel segments with installed power up to about 25MW. This technology exist today and can be expanded to drilling vessel of this range.
- MV variable AC systems with variable frequency switchboard operation for MV applications on larger vessels with installed power capacity above 25-30MW.

Techniques for operating and AC power plant with variable frequency (40 to 60 Hz) does exist, as most of the main power consumers like thrusters and drilling are supplied via frequency converters and thereby independent of input frequency. Other consumers requiring fixed 60 Hz (or 50Hz) network will be supplied via static converters keeping a constant voltage and frequency. All of these solutions can be combined with energy storage, and closed ring operation.
A case study showing the potential savings (from 10 to 30%) by applying variable speed generation for a drilling vessel operational profile example.

Abbreviation / Definition

AC – Alternating Current
DAC – Dynamic AC
DC – Direct Current
DOL – Direct Online
DP – Dynamic Positioning
GT – Gross Tonnage
LV – Low voltage (690V AC or 1000V DC)
MV – Medium Voltage (6,6kV or 11kV)
OSV – Offshore Support Vessel
PSV – Platform Supply Vessel
VSD – Variable Speed Drive

Introduction

Power plant design for DP drilling vessels have gradually improved in both safety and efficiency the last decades. Several articles are published on this subject from power and thruster drive essentials [1], phase back systems and improved engine utilization [2], [3] and through the latest years with focus on closed bus operation [4] and introducing energy storage [5]. The trend has been from the safety focus in mind to add energy efficiency into the picture. This article introduce a new feature of variable speed power generation, adding to the element of efficiency and the “green drilling unit” concept.
There are several ways of achieving variable speed generator engine operation, and most commonly would be either by DC distribution of main power or by allowing a variable frequency at the main switchboards. Either ways, the main motivation is the fuel saving potential that lies within the possibility to run diesel engines in a fuel-optimal condition even at lower load by reducing the speed.
Other benefits in the terms of maintenance (reduced number of shaft revolutions), reduced noise level, smaller engines, etc. are adding to this. Further, there are aspects of equipment selection, and

optimization, for example using smaller “high speed” engines that operates most of the time in medium speed condition.
The optimization key lays with the operation profile and by that the fact that most of the time DP vessels actually work in clam weather and low load conditions.
For smaller types of offshore DP vessels, DC distribution technologies is already emerging as for example the ABB’s Onboard DC Grid concept [6], enabling variable generator speed operation. Up to 27% fuel saving have been reported for certain operation modes of a DP Supply Vessel having variable speed operation with dc grid distribution.

In this article, the focus will first be on the potential of the concept itself, also looking at several vessel types and already sailing vessels. Then various solutions for drilling vessels will be presented, among them a low voltage (LV) DC grid concept for smaller to mid-size segment and then MV variable AC concept for the larger units. A case study will illustrate the saving potentials.

Variable speed generation operation of DP vessels

Traditionally electric propulsion vessels are designed with a fixed frequency/voltage power plant consisting of multiple generator engines. The thrusters and propulsors are driven by variable speed converter systems for accurate control of propeller RPM and related power/thrust values. The basic idea of optimizing the running conditions is to turn on and off gensets according to required load demand. However for DP vessels of class 2 or higher, the safety and redundancy requirements would yield more generators than necessary online, and hence engines running outside their fuel-optimal design points. This issue has been addressed the last years by allowing design and operation with closed bus tie breakers between redundancy zones.
Another way to tackle this challenge is by allowing the generators to run with variable speed within a window from about 60% up to rated speed. This will have impact on the electric power plant design either by distributing by DC or let the main AC system have a varying frequency. In a DC distribution system each generator is connected to a rectifier, and thereby decoupled from each other and electric power can be distributed independent from the actual generator speed. This system has been successfully implemented in several low voltage (LV) applications, and one example with a platform supply vessel (PSV) with DP class 2 will be shown as reference later in this section. Even though this method has been successful for LV systems it has been a challenge to design a similar system for larger capacity systems requiring higher voltage levels of 10 to 15 kV. Recently ABB launched their variable AC solution Dynamic AC system (DAC) for cruise vessels operating with 11kV main power plant and implementing variable speed generation system and thereby also a variable frequency main power plant (40 to 60 Hz). Both LV DC grid solutions and variable AC solutions will further in this article be presented and discussed for DP class drilling vessels.

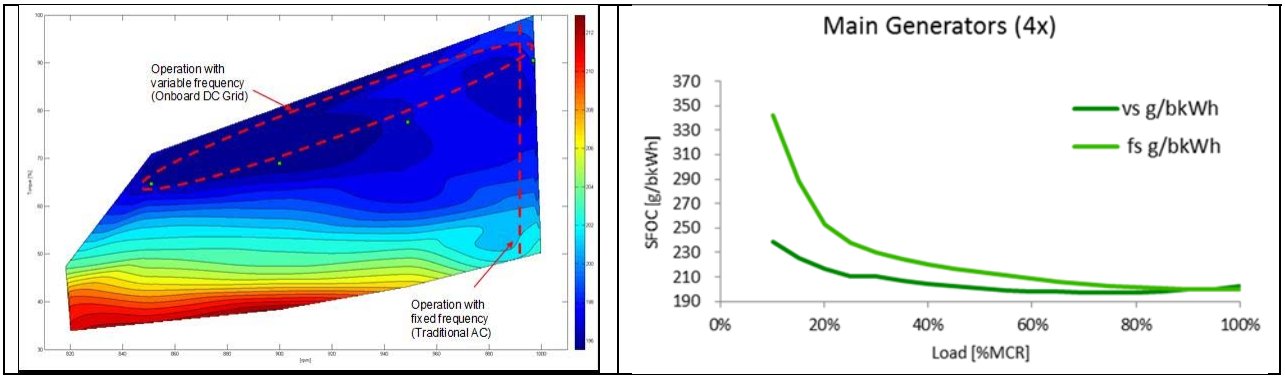


Figure 1: Engine performance in fuel consumption in fixed speed vs variable speed operation

Regardless of which technology is used, the potential of fuel optimization by running variable speed is shown in Figure 1. Based on this figure there is for example a theoretical fuel saving potential of about 15% at 30% loading and increasing for lower loadings. It should be pointed out that there are different curves and different potentials depending on engine type and make, and each project should be evaluated based on the selection for that project.

Drill ships and semi-submersible rigs are designed and optimized for drilling operations in DP mode within a certain weather window. The two main group of power consumers are the drilling equipment and thruster system. While the drilling equipment is operated and consuming electric power independently from the weather conditions (except active heave compensation), the thruster power consumption correlates with the weather conditions. This means the design of thruster drive system is optimized around the maximum allowable weather, and in addition designed for transit capability when moving the vessel between wells, both high power demanding operations. However, looking at operational profile on a yearly basis, most of the operation time is in DP with relative calm weather conditions. Figure 2 illustrates the usage of thruster of a drillship in one year operation. The thruster drive motors are rated at 750 RPM, but as can be seen from the figure most of the operation is below 300 RPM which correspond to less than 7% of rated power consumed (assuming cubic power/RPM propeller curves).

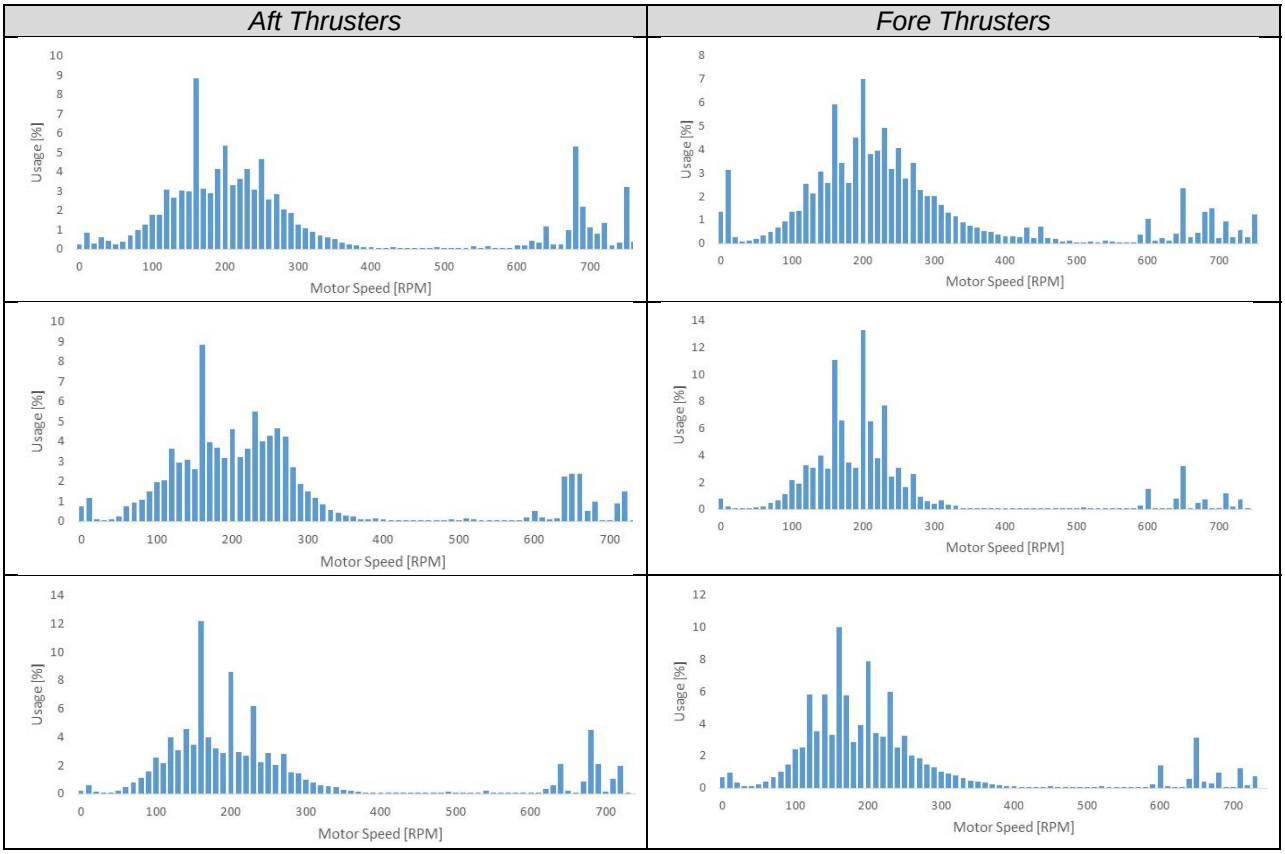


Figure 2: Thruster drive RPM usage in one year operation (2015) for a drillship with 6 thrusters.

This operation is in DP mode. Then the next level of RPM operation is between 600 and 700 RPM which corresponds mostly to transit operation.

Looking at the vessels operating profile (speed over ground) for one year it is operating about 90% in DP and 10% in transit see Figure 3.

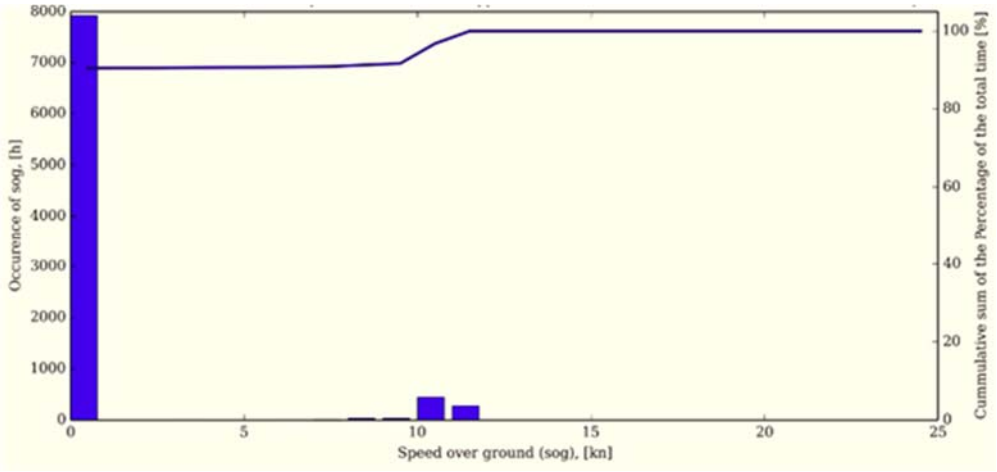


Figure 3: Cumulative speed over ground for a drillship (1 year).

Based on these two figures it can be stated that for this typical example drillship the consumed power on the thrusters are less than 7% of rated for 85% of the operation time.
This affects also the generator loading as certain minimum numbers of generators are online due to redundancy requirements in DP operation. Adding on the average drilling (about 4MW) and auxiliary (2MW) loads the generators are loaded around 30% or less for a system with 6 x 7,5MW generator capability and 6 x 5MW thruster capability and assuming 3 running generators.

As an illustrative example of how the DC grid technology is designed for smaller vessels a typical configuration single line is shown on Figure 4.
Typical for this type of the vessel is the varying power demand in the different operation modes with low power utilization of the diesel generator sets. The major operation modes are DP, Steaming, In-Port (Harbour) and Stand-by, see Figure 5. Except from steaming mode where the diesel engines are usually operated at their optimum, in the other modes the average engines load is rather low with a loading factor below 50%. The low loading might be a consequence of a general low power consumption in the individual modes and/or due to operation mode depending requirement for redundancy in the power generation plant. This low loading when operated at fixed speed causes the engine to operate with a higher specific fuel oil consumption as discussed (Figure 1).
With the given design operation profile the difference in the specific fuel consumption characteristic of the diesel engine between fixed and variable speed operations corresponds to a 10% reduction in overall fuel consumption when operated with variable speed. With most of its operational time running at low load and related low speed the additional benefits of the engine variable speed operation are reduced noise and maintenance (less rotations on each cylinder). Measurements and test conducted were conducted on a specific vessel Dina Star, a 93 meters long, 4,800 GT type MT 6015 PSV, a multipurpose oil field supply and construction vessel with DP class 2. These measurements confirmed the theoretical potential of variable speed operation of the diesel engines and verified reduction of specific fuel consumption of up to 27% savings in DP modes and average 14% on the total profile measured. Measurements also confirmed that due to the reduced engine speed the noise level has been reduced by 30% [7].

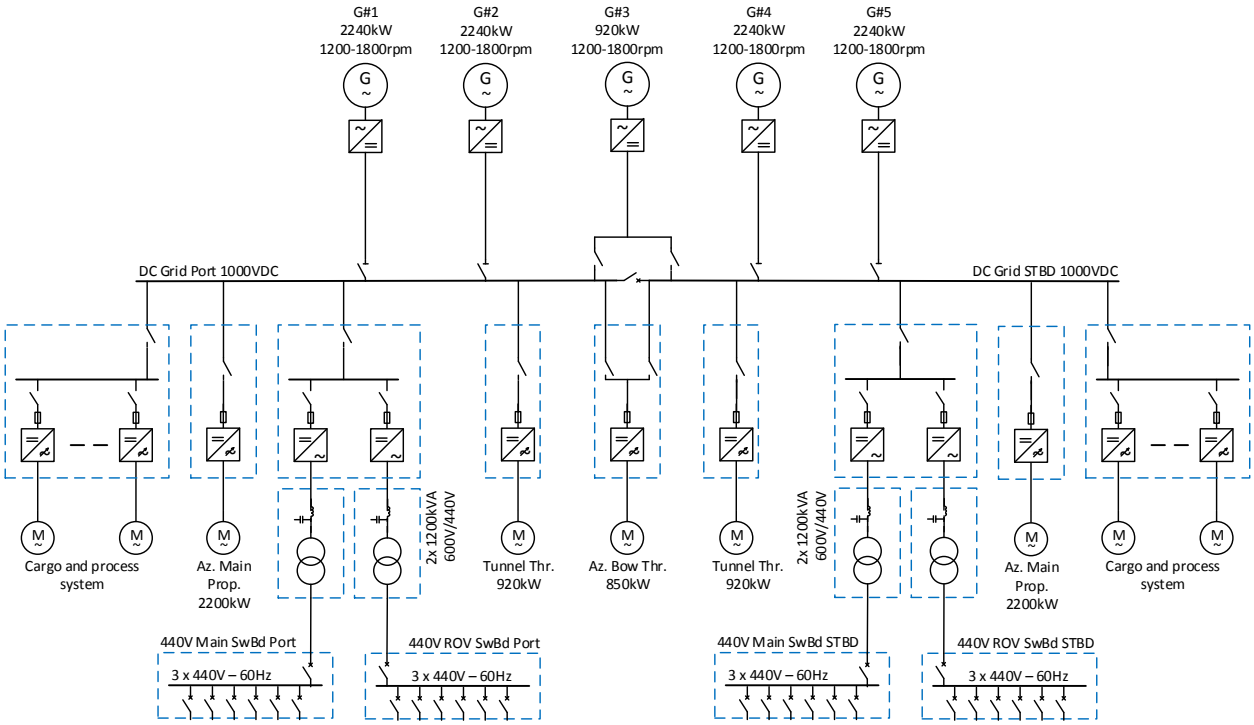
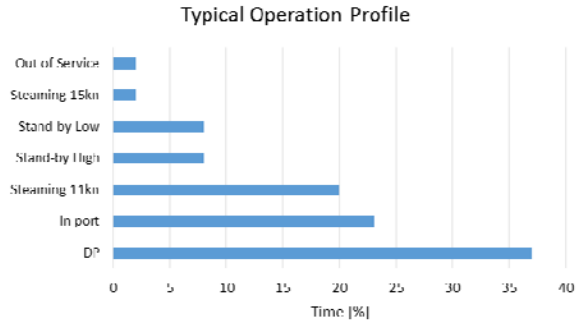


Figure 4: DC grid principle power single line, OSV vessel



Mode	Time [%]	Power Demand [kW]
DP	37	2128
In port	23	168
Steaming 11kn	20	1836
Stand-by High	8	1000
Stand-by Low	8	755
Steaming 15kn	2	4260
Out of Service	2	0

Figure 5: Operation Profile and Engine SFOC curve

Solutions for Drilling Vessels

In this section the two proposed solution for variable speed generator operation will be explored for drilling vessel application. There are many ways of configuring and designing the systems, so these proposals should be taken as examples only, as modification and details must be settled individually for each project. Basically we are presenting the LV DC grid solution for the mid-size segment (less than 20MW installed power) and the MV variable AC solution for the larger scale segment (40 – 50 MW installed power). It should be noted that above mentioned power ratings by no means is restricted limitations, and the solutions may be used also outside these.

Mid-size segment with DC Grid distribution

In mid-sized drilling units the size of the installed power plant, usually below 20MW, is still in a range where LV DC distribution is well suited. By using LV DC distribution the design principles of power system design and integration methods of main sub systems as developed for offshore supply vessels can be applied directly to mid-sized drilling unit. Similar to the offshore supply vessels, the drilling units main consumers are variable speed controlled drive systems (drilling, thrusters, etc). Also characteristic for this vessel type is the highly variating power demand and fast dynamic load changes.

With the generators individually connected to the DC distribution the engine speed can be optimised freely based on the load of the engine. With LV variable speed controlled equipment as the main power consumers, the direct supply of DC power through the DC distribution simplifies the integration of those equipment. This reduces power conversion steps as well as risk for network disturbance usually to be considered with use of large VSD system in AC networks, as for example by induced harmonic currents. DC distribution is also an enabler for simple and more functional integration of energy storage systems. This has been highly discussed and studied in the industry the last years both for the purpose of fuel saving and increased safety.

Figure 6 gives an example layout, with 6 generators grouped in two parts, 4 thrusters, a drilling switchboard and feeders to AC distribution networks. Since there is still need for fixed AC distribution voltage, these are fed by separate static network converters. These are based on IGBT inverter technology as used in VSD application and is equipped with special control software to produce network line voltage (fixed frequency) including network control and protection functions. LCL filter for clean power supply and power transformer to adjust to design voltage level are also added. Energy storage is included in the drilling drive line-up, but would be able to contribute to the whole power system as all the DC circuits are connected via bi-directional connection units. Basic function is dynamic support to avoid the engines running very fast up and down in speed due fast load variation in the drilling VSD system.

With dynamic changing power consumption in operation modes it is difficult to define a fixed load profile for vessel. Based on the electrical load analysis some basic estimation can be done, see **Error! Reference source not found.**. To estimate the power consumed by the thrusters a moderate sea-state is considered. Considering the assumed power consumption and variation in the operation modes as well as given engine size of 3000kW it is supposed that in tripping and drilling mode the power generation plant is configured with four engine running and with two engine running in standby mode. This lead to an engine load variation of 37% to 67% between defined min. and max. power demand.
Comparing the specific fuel oil consumption of a standard ship medium speed diesel engine at fixed speed as used today in diesel electric power plants with a new generation medium speed common rail diesel engine which is operated with variable speed there is significant improvement in specific fuel oil consumption. Because of speed reduction at low engine load the specific fuel oil consumption in this example can be reduced by up to 18,5% at 37% engine load and 11% at 67% engine load, see **Error! Reference source not found.**.

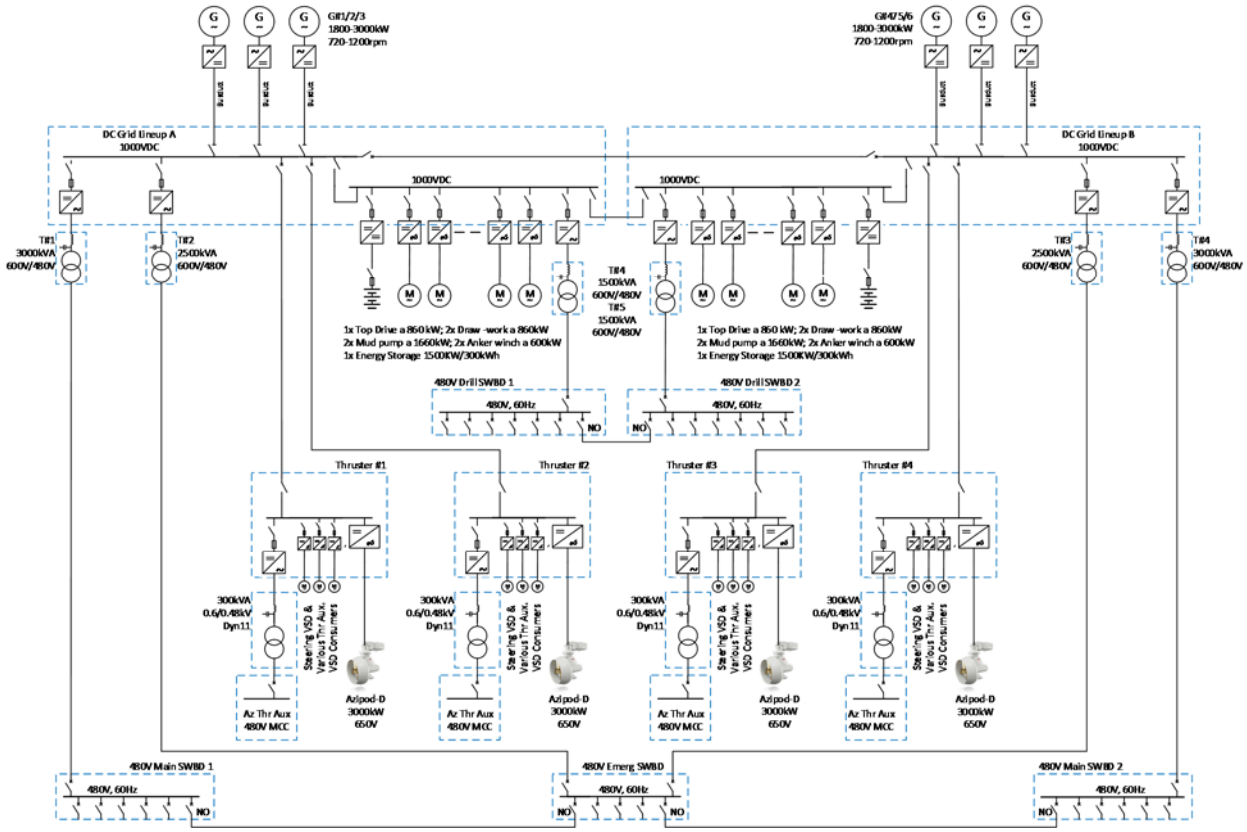


Figure 6: Power Single line example of Mid-size Thruster Assisted Moored Drilling Unit

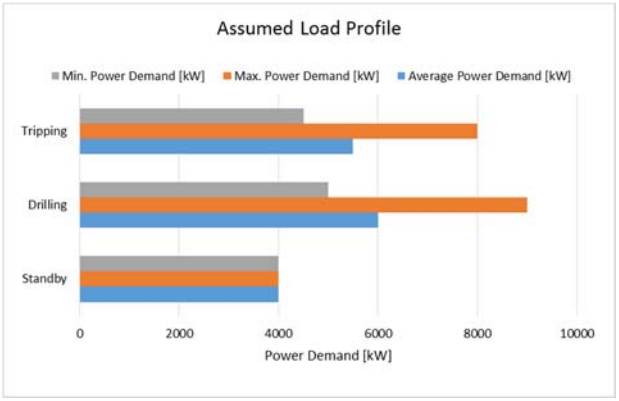


Figure 7: Mid-size vessel Load Profile

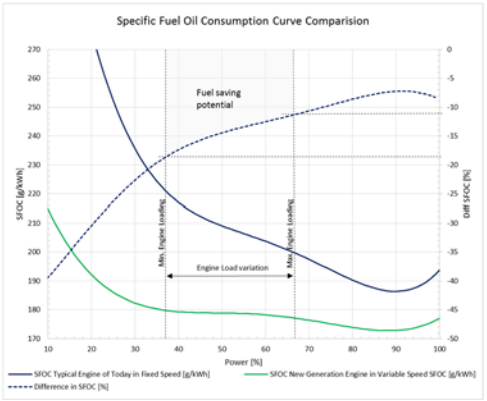


Figure 8: Engine SFOC characteristic, comparison and saving potential

Large size segment with MV variable AC

In this segment the installed power plant in the range of 40 to 50MW. The configuration usually have six medium speed diesel generators rated in the range of 7-8MW, six azimuth thrusters rated at around 5,5MW for DP operation and a two or three drilling system with a total installed power of ab. 20MW. For redundancy purpose the power system is divided into three independent sub systems, see Figure 9 for a principle single line. The main distribution system for such high power installation has to be realized on a high voltage level, usually 11kV, to keep load and short circuit currents within a practical level. Typical for this type of the vessel is the varying power demand in the different operation modes and redundancy requirement in the power generation plant based on running machinery which causes overall low power utilization of the diesel generator sets.

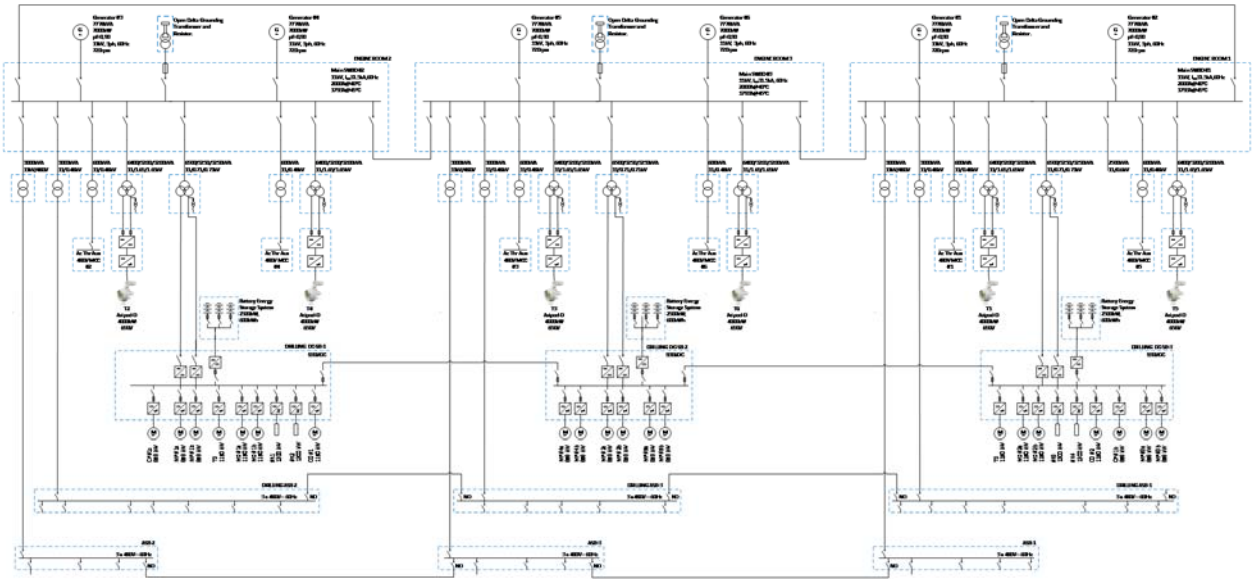


Figure 9: Drillship typical AC power single line

Using DC distribution as applied in offshore supply vessels and proposed for mid-size drilling units is not feasible on high voltage levels due to unavailability of critical protection and power conversion system components. To employ the advantage of engine variable speed operation, the distribution system and main consumers must be capable to operate on a variable network frequency. AC distribution networks capable of operating with variable network frequency is already used in marine system mainly in connection with shaft generator powered electric systems. ABB have recently launched a concept for MV AC variable speed generation system named Dynamic AC (DAC). The system AC voltage is kept constant over the design frequency operation range. The practical frequency operation range is in an area from 40Hz - 60Hz where the actual used frequency operation might be defined based on optimizing process considering equipment cost and size as well operation savings.

Marine medium speed diesel engines types are available in variants for fixed and variable speed operation. With defined speed and frequency range the electric generator can be designed to supply a constant voltage over the entire range. The MV variable AC main distribution switchboard can be designed with the same advanced power system protection features and configurations as used in a modern MV main switchboard operating with fixed frequency. This allows for a safe, flexible and efficient power plant configuration optimized for the actual operation mode of the vessel. Same as for power system with fixed network frequency, closed bus and ring bus as well and open bus configurations are possible. Active and reactive power load sharing between paralleled generator sets in a MV Variable AC power system is based on the same principles as used in traditional fixed frequency power systems.

Thruster and drilling variable speed controlled systems are the main power consumers on a drillship and based on frequency converter technology. Characteristic for the most common used frequency converter topology is a rectifier unit which converts the supply AC voltage into DC voltage. The DC voltage level is only depending of the input AC voltage amplitude which is kept constant in variable AC power system. Especially passive (diode) rectifier units are capable to operate in a wide supply voltage frequency range. This makes the frequency converter suitable to be directly supplied by the variable AC main MV distribution switchboard.

Also a range of low power equipment (e.g. low power frequency converter, heaters and certain DOL operated pumps) is capable to operate in a power system with variable network frequency. If advantageous for the system design those equipment can be supplied by a separate LV distribution system directly supplied from the MV variable AC main distribution switchboard.

The LV drilling VSD system is usually based on a multi-drive configuration. In a multi-drive configuration the common DC-link is used to distribute DC power to individually controlled inverter-motor sets. The DC-link can be seen as the simplest variant of a DC distribution system. The multi-drive DC link can be extended with LV DC grid technology features to form a LV DC distribution switchboard. The DC distribution system can be centralized or distributed. DC distribution simplifies the integration of various high and medium power frequency converter controlled consumers. Frequency converters not only simplifies the integration of consumers into a MV variable AC power system, but also due to the variable speed control, improve the energy efficiency and by that the power consumption of consumers like pumps and fans. The DC distribution simplifies also the integration of energy storage systems.

Even if a big number of electrical equipment might be suitable for supply voltage with variable frequency or can be supplied from a DC distribution system there is equipment which depends on a supply voltage with fixed frequency. Clean power converter are used to generate LV distribution power system with fixed voltage and frequency in a quality which fulfils marine stands and rules. The configuration principle of MV variable AC power system can be seen in Figure 10.

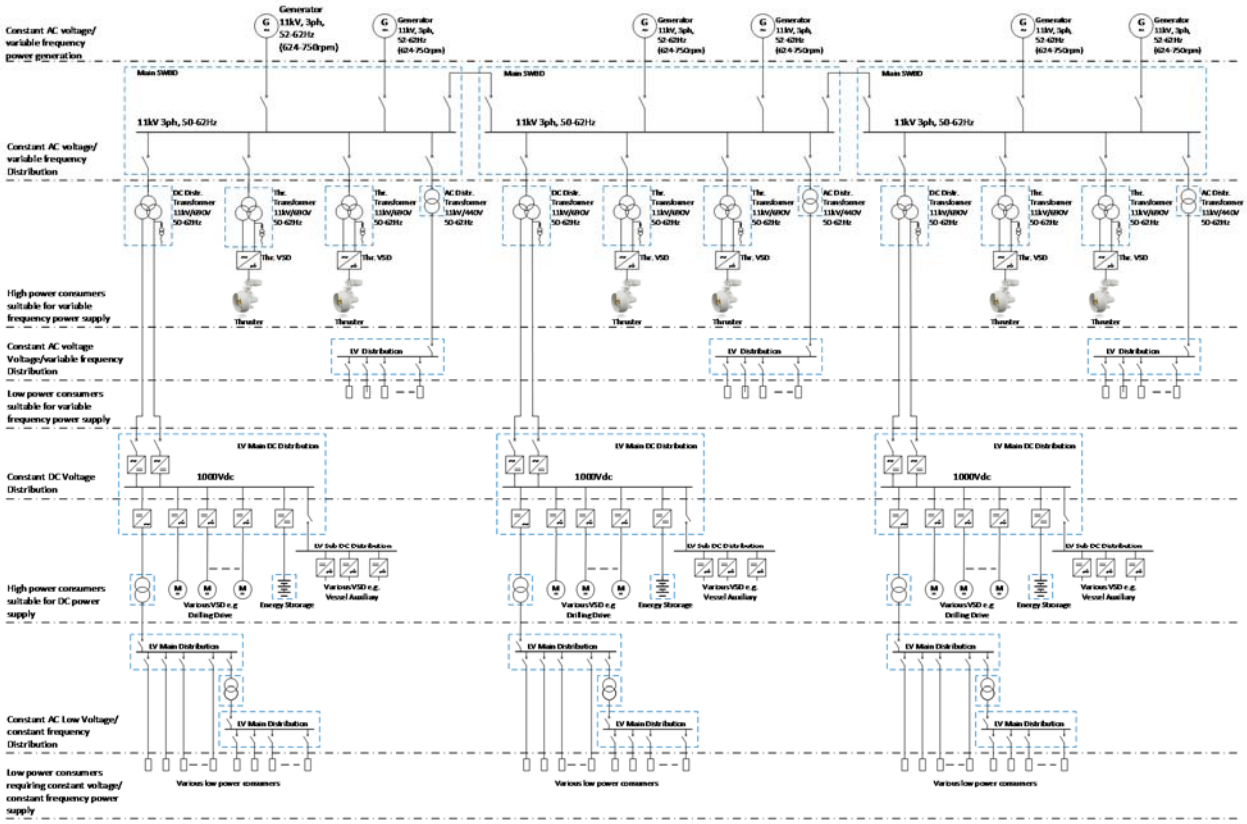


Figure 10: MV variable AC principle configuration for drillship

Electromagnetic equipment like power transformers and generators which are connected to variable frequency distribution systems need to be designed accordingly. The low frequency, constant voltage operation affect the electromagnetic circuits in transformers and generators and thus they need to be slightly over dimensioned. For LV AC distribution, static converters generates the voltage with a fixed frequency and amplitude similar as required for the DC grid solution.

Same as for mid-size drilling units with dynamic changing power consumption in operation modes it is difficult to define a fixed load profile for vessel. Based on the electrical load analysis some basic estimation can be done, see Figure 11. To estimate the power consumed by the thrusters a moderate sea state is considered.

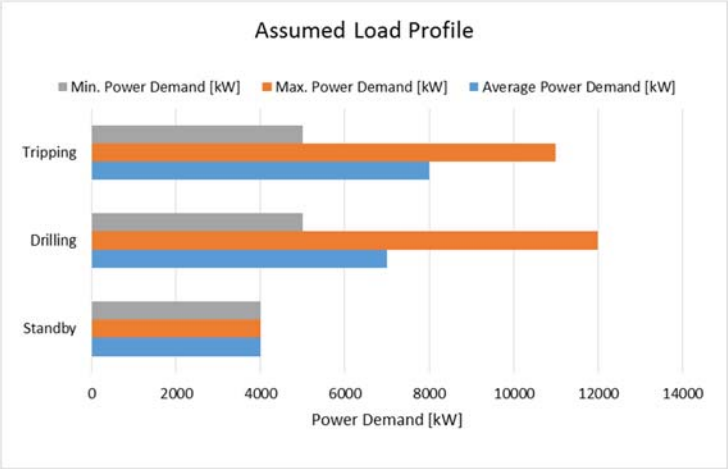


Figure 11: Large size drilling vessel Load Profile

Considering the assumed power consumption and variation in the operation modes as well as given engine size of 7600kW it is supposed that in tripping and drilling mode the generation power plant is configured with three engine running and in standby mode with two engine running. This lead to an engine load variation 17,5% to 52,5% between defined min and max power demand.
Comparing the specific fuel oil consumption of a standard ship medium speed diesel engine at fixed speed as used today in diesel electric power plants with a new generation medium speed common rail diesel engine which is operated with variable speed there is significant improvement in specific fuel oil consumption. Because of speed reduction at low engine load the specific fuel oil consumption in this example can be reduced by up to 34% at 17,5% engine load and 14% at 52,5% engine load, see Figure 12.

Figure 13 shows a proposal for a MV variable AC power system single line for a drillship. The power generation plant consists of six diesel-generator sets which can be operated in a speed range of 624rpm – 750rpm (52Hz – 62Hz) with a rated power @750rpm of 7,6MW. The switchboard configuration follows the redundancy design concept of the vessel with three redundancy zones, where each zone is assigned an individual self-contained MV switchboard. The MV switchboard can be operated in split-, closed- or ring bus configuration. Six 5MW podded azimuth autonomous thruster system are considered for propulsion and DP operation. Each thruster drive system includes inverters for the speed controlled thruster motor, the speed controlled electrical steering gear motor, cooling pumps and static converter to generate a local LV AC distribution for low power auxiliary system. Three LV DC distribution system are supplied by two 6,5MVA rectifier units providing power to the drilling VSD system, VSD controlled ship auxiliary equipment and two 2,5MVA static converters generating power to a LV AC ship distribution and LV AC drilling distribution system. The LV DC distribution includes energy storage for dynamic support of diesel-engine during fast and high power load variation in drilling VSD system. The LV DC distribution systems can be interconnected.

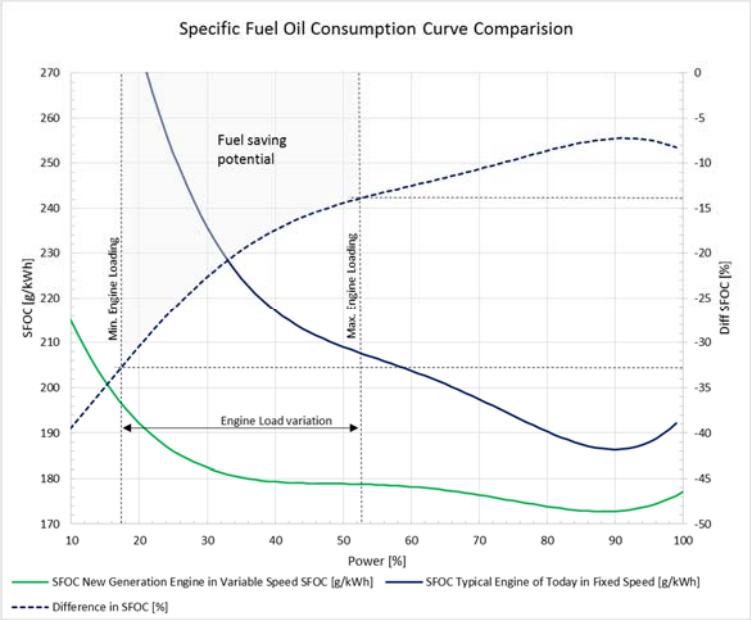


Figure 12: Engine SFOC characteristic, comparison and saving potential

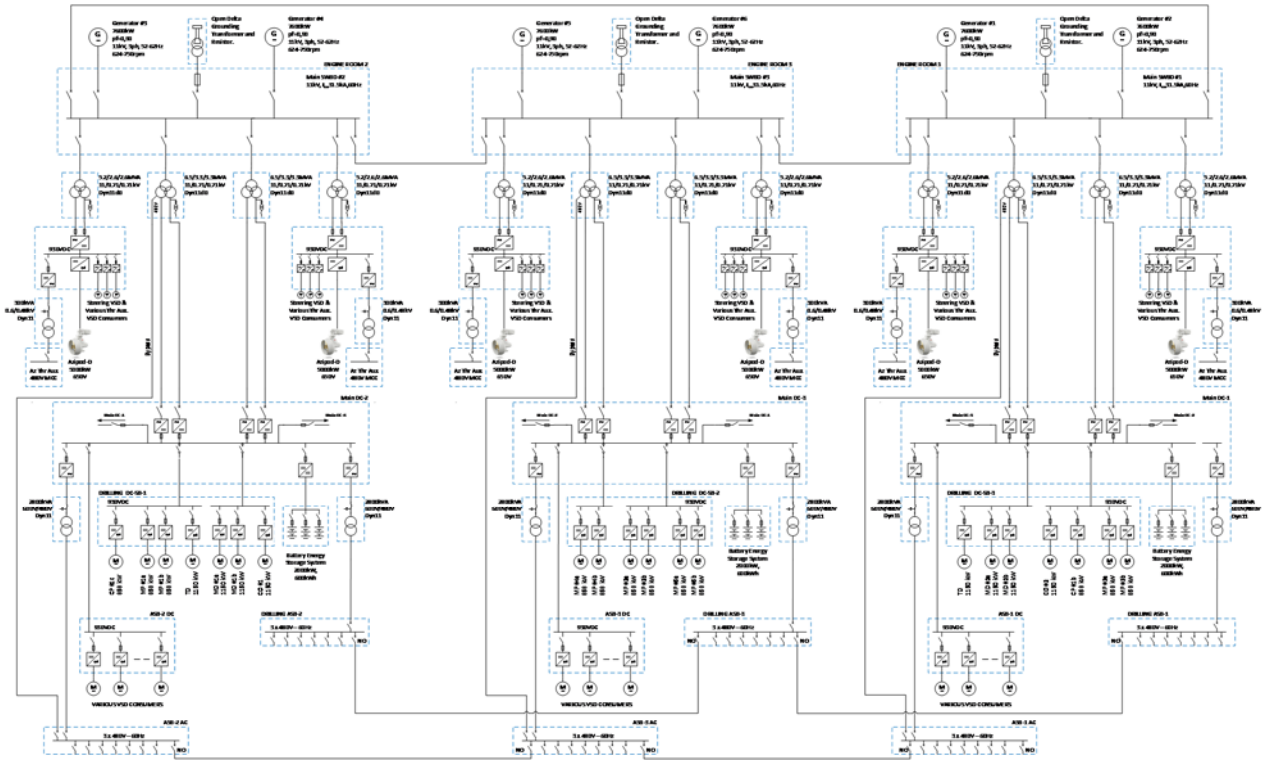


Figure 13: Drillship power single line for MV variable AC

Case study

Based on the assumptions in previous sections there is a significant potential for energy saving by operating with variable speed. Specially, if we consider the difference between modern common rail diesel engines optimized for variable speed, and todays fixed speed engines. In this section we make one case study for an example configuration based on real operational data from one week of drilling operation, see Figure 14. The power log show a typical power variation of 6MW, with extra up to 10MW. The base load varies between. 6-8MW and is mainly contributed by the thruster as well as auxiliary systems.

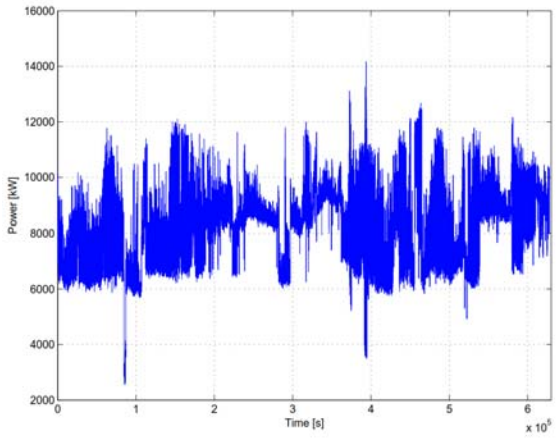


Figure 14: Power plant data log of one week drilling operation

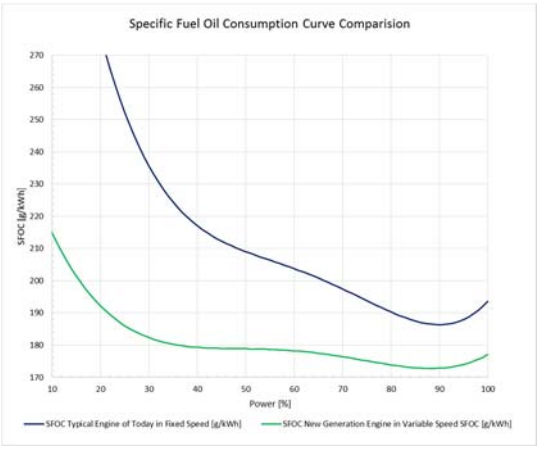


Figure 15: SFOC characteristic of compared engines

Considering a closed bus HV switchboard operation and equal load sharing between parallel diesel-generator sets the fuel consumption can be calculated based on the available SFOC characteristics of the engine to be compared, see Figure 15.
Table 1 lists the fuel consumption calculation for the engine type and operation as well running diesel-gen set configuration. It is clear that with the variable speed operation on a common rail engine the 61t fuel saving when comparing the three generator configuration is substantial. Another observation is that the difference by running 2 or 3 generators are less in variable speed operation, while quite substantial in fixed speed operation. This again indicates that variable speed operation can be considered as alternative to closed bus operation with respect to efficiency.

Engine/operation type	Q'ty Gen sets	Fuel consumption [t]
Fixed speed operated typical medium speed marine engine	3	318,8
	2	294,7
Variable speed operated common rail engine	3	257,6
	2	254,9

Table 1: Fuel consumption comparison for a one week drilling operation

On the equipment and installation side the additional cost lies mainly with the generators, which need to be dimensioned for variable frequency, and the island converters feeding the fixed frequency distribution network. The additional cost should be less than 10% on the electrical power and propulsion plant investment, and very roughly additional footprint in the range 50 to 60 square meter, but this includes also energy storage, which is also highly discussed in today's classical systems. For detailed calculations and comparisons each case has to be considered separately as there are many factors influencing the final and optimal design.

Conclusion

Variable speed power generation systems have been investigated for DP drilling vessels. Two versions have been presented, one LV DC Grid solution and one MV Variable AC solution. Either way, by studying operational profiles and actual loading on thrusters and generators a significant fuel saving potential is identified by this operation. This is basically due to the fact that these kind of DP vessels most of their operational time is in low load, calm weather conditions. Further, the engine fuel curves gives the potential if you can vary the engine speed with consumed power. LV DC Grid applications is already in use in smaller vessels, and an example on how this can be extended to mid-size drilling vessel segment is presented. Further for the larger size vessel a variant of MV variable AC is shown, allowing the main switchboard frequency to vary between 40 to 60 Hz. In practice a smaller variation window may be more realistic for further optimizing equipment selection. From other vessel experience a fuel saving potential of up to 27% has been recorded for certain operation modes. More average savings would be expected in the range 10 to 15%, and this is also in the range as calculated for the case study in this paper.
On the equipment side the variable speed operation will lead to some additional investment cost as generators need to be dimensioned for a variable frequency, and separate island converters are needed for the fixed frequency AC distribution. For variable generator speed operation ABB launched Onboard DC Grid in 2011, and Dynamic AC for MV application earlier this year. Both of these system can be extended also drilling applications and fit very well with DP operational profiles. This system is adding on to benefits already presented and discussed in the last years related to closed bus operation and energy storage systems.

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