

The sound of silence: permanent magnet machines for silent vessels

PM motors represent a simple and reliable mechanical solution for achieving quieter vessels, argues Jussi Puranen of Finnish technology firm The Switch



Figure 1: Generator on the left during final assembly and before painting, and the motor on the right.

A diesel-electric propulsion system, based on the power station principle and electric propulsion motors, is already the number one choice for many types of vessels, due to its benefits over diesel-mechanical propulsion. The main benefits of diesel-electric propulsion are reduced fuel costs, redundancy, excellent torque-speed characteristics (including fast dynamics), and reduced vibrations.

By using a permanent magnet (PM) machine as a propulsion motor, excellent efficiency can be achieved, resulting in fuel savings for gensets. Further benefits of PM technology are space/weight savings and increased reliability due to simple mechanical construction.

With the proper design, PM machines can also be utilised in so-called silent vessels, requiring very low structural-borne noise (SBN) levels. Typically, such vessels have used DC, induction or electrically excited synchronous motors, but low SBN levels can be also achieved with PM technology.

Reduced fuel costs

Especially with ships that do not travel at full speed most of the time, diesel-electric propulsion results in significant fuel savings, as some of the power station gensets can be shut off when operating at lower speeds,

resulting in greatly reduced specific fuel-oil consumption (sfoc). Variable-speed gensets provide even more fuel savings, meaning that instead of supplying genset power directly to the grid in which only constant speed is allowed, it is supplied through the frequency converter, thus allowing variable speed for the genset, depending on power demand.

It is well known that diesel engine-driven generators operate at maximum efficiency at partial speeds. At the nominal point when a ship is moving at rated speed, the efficiency of a diesel-electric system is typically lower than that of a diesel-mechanical system. But in vessels which operate a large part of the time at reduced speeds, this is compensated by reduced fuel consumption at partial load. Vessel types benefitting the most from electric

propulsion include large cruise vessels, and various kinds of vessels with dynamic positioning (DP), such as offshore supply vessels (OSV), drilling vessels, dredgers, shuttle tankers and cable-laying vessels. By using PM machines instead of conventional machine types, such as induction or electrically excited synchronous machines, fuel savings can be further increased, since losses related to magnetisation in the generators are eliminated. With direct-drive PM propulsion motors in particular, the difference compared to electrically excited synchronous machines is significant.

Increased redundancy

With diesel-electric propulsion, instead of using a single large 2-stroke main

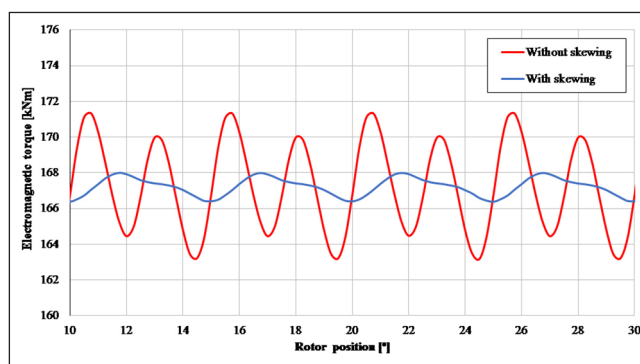


Figure 2: Torque ripple of a propulsion motor at full-load with and without skewing. As can be seen, there is a significant drop in the torque ripple when skewing is applied

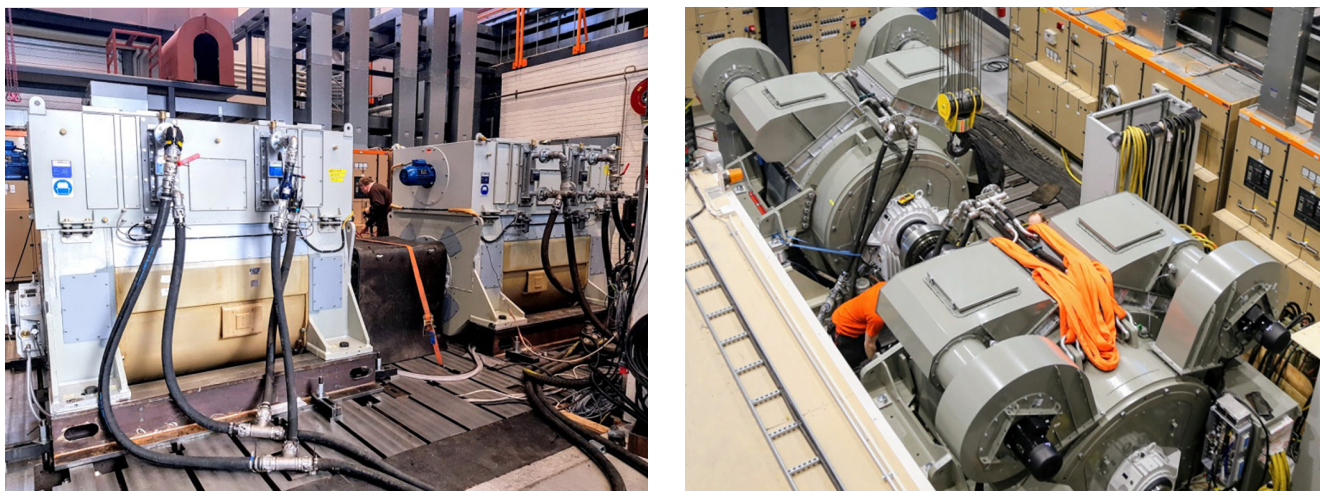


Figure 3: Machines in the full-load back-to-back test at The Switch Lappeenranta Factory. Generators on the left and motors on the right

engine as a propulsion power source, power generating sets are divided into several parallel independent units. Propulsion power can also be divided into two or three independent units, meaning that a failure in any single generator/motor will not result in total loss of power.

Often half the power, as a minimum, is left in case of a fault in one of the motor/generator units. Even if 50% of propulsion power was lost, a ship would still be able to move with around 70% of its nominal speed. Instead of just using parallel motors/generators, redundancy can be further increased by using dual-winding motors or generators.

A common practice at The Switch is to divide the stator windings into two, three, or more sub-windings that can operate independently when supplied via their

own frequency converter. This means that if a frequency converter fails when it is connected to a single sub-winding, only that part need be switched off, and the PM machine can keep operating with the remaining healthy converter with reduced power. This significantly increases the redundancy of the system, and results in higher available propulsion power in case of a frequency converter failure.

Torque characteristics

The fact that conventional diesel engines produce maximum torque only in a very narrow speed range causes significant problems in vessels needing high torque at low speeds – for example in ice breakers. This is the main reason why diesel-electric propulsion is a superior choice in such

applications, as electric motors can supply full torque from zero up to rated speed.

Originally DC motors were used since they were the only motor type able to produce high torque at low speeds. But their problems were huge weight and size, poor reliability due to complex mechanical construction, and their constant need for maintenance due to commutators and complexity. Nowadays they have been almost entirely replaced in propulsion drives by AC motors and frequency converters, which can produce the same excellent torque characteristics with fewer problems.

Furthermore, when direct-drive PM motors are used for propulsion, the dynamical performance of the shaft line will improve, due to the very low rotating mass and inertia of a direct-drive PM motor. The inertia of a PM motor can be a tenth of the inertia of electrically excited synchronous machines, the main alternative in direct-drive propulsion, which improves the dynamic performance significantly in a PM-motor-based system. This is important in ice breakers, as a cogent example, where it is imperative to rapidly clear the ice to avoid blocking the propellers.

Reduced installed power

Certain vessel types, such as LNG ships and floating storage regasification units (FSRU), have a very high power demand when the vessel is not moving, due to LNG loading/unloading or cooling. This means that the power plant of such ships uses high power consumption even with no propulsion power. Since propulsion power and standstill

Table 1: Variable speed PM genset and propulsion motor for a silent fishing vessel

	Generator	Propulsion motor
Rated power (kW)	3055	2250
Rated speed (RPM)	720	130
Rated voltage (V)	690	690
Rated current (A)	2750	2100
Rated frequency (Hz)	36	26
Measured efficiency (%)	97.7	96.6
Cooling type	IC8A6W7	IC8A6W7
Weight (t)	12	19
Bearings	Sleeve bearings	Sleeve bearings
Certification	DNV-GL (Silent F)	DNV-GL (Silent F)

power are not needed at the same time, using diesel-electric propulsion reduces installed power needs considerably, compared to conventional diesel-mechanic propulsion.

For example, an LNG ship with 20MW of propulsion power and 10MW of standstill power would need a total of 30MW of total power capacity – 20MW from the mechanical propulsion source and 10MW of electric power from the power plant. In the case of a diesel-electric system, total power demand from the power plant would be 20MW plus the hotel load of perhaps a few

MW and margins – significantly less than a diesel-mechanical system.

Reduced vibrations

In vessels requiring a low level of underwater radiated noise, such as fishing, research and naval vessels, it is paramount to minimise the SBN of the propulsion machinery. Since diesel engines and gearboxes produce high levels of vibrations and noise, it has been common to utilise direct-drive diesel-electric propulsion in such vessels. The main reason for doing this is that the diesel engine that drives the

gensets can be decoupled from the propeller, significantly reducing underwater noise.

In the past, DC motors were used exclusively, since, in addition to the good low-speed torque characteristics discussed earlier, they produced very smooth torque, causing less underwater noise than AC motors. With modern frequency converters based on insulated-gate bipolar transistor (IGBT) technology, a very low level of current ripple can be achieved.

Nowadays, when combined with properly designed AC motors, this has enabled electric drives based on AC rather than DC technology in silent vessels. Typically, AC propulsion motors have been either induction or electrically excited synchronous machines, since they are well-known technology. The drawbacks, however, are reduced efficiency and bigger size and weight.

PM generator and motor

During the spring of 2018, The Switch supplied variable-speed PM gensets and direct-drive propulsion motors for a fishing vessel having a DNV-GL Silent F notation. The main data of the machines can be seen in Table 1 and Figure 1.

In order to minimise airborne and structural-borne noise levels from these machines, the electromagnetic vibration level was reduced by optimising the rotor pole shape and by applying skewing for the magnets. The cogging torque amplitude (the tendency of the magnets to align themselves with the stator teeth, of the propulsion motor, which is more critical since it is directly coupled to the propeller) was only 0.15% of the rated torque.

At full-load, torque ripple always increases from the no-load value, or cogging. This is due to the fact that under load, stator current harmonics will cause their own torque harmonic components, causing the torque ripple to increase. Regarding the propulsion motor, torque ripple amplitude at full load was still only 0.48% of the rated torque, imparting very low torsional vibrations to the propeller and giving a low underwater radiated noise level. To illustrate the effectiveness of magnet skewing, it reduced the torque ripple from 2.5% down to 0.48%. Since skewing has a very limited downside and needs only slightly higher current, it should always be applied to any motor design. Figure 2 shows the torque ripple of

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a propulsion motor at full-load, with and without skewing.

Sleeve bearings were used in both machines to keep mechanical excitations low. Low-speed cooling fans were used to limit audible noise. Resilient mountings, or 'mechanical dampers', were used for connecting the machines onto the test bed, since they were to be used in the final application as well, and typically they have the biggest impact on structural-borne noise emitted from the motor.

SBN levels were measured with and without resilient mountings, to determine their exact impact. Furthermore, measurements were repeated at various load levels. On the frequency converter side, tests were done with and without the LC-type output filter, to verify its effect.

The purpose of converter output filtering is to reduce high-frequency (typically in kHz range) current harmonics that are due to converter pulse-width modulation (PWM), and therefore to reduce both structural-borne noise and audible noise.

Measurement results

Measurements were taken for all three directions – vertical, transverse and longitudinal – by using OROS OR36 8-channel signal analyzer and NVGate software. Accelerometers were glued to the foundation below the machine foot, all transducers were calibrated before the tests, and background noise was measured. The mobility of the test bedframe was measured, and results were corrected according to common practice.

Measured SBN levels are presented in Figures 4 and 5 below for both the motor and generator. Due to test-bench limitations, measurement of SBN levels at full-load was not possible for the generator (PMM 630), so it was carried out only at no-load. Still, SBN levels of the generator are not that critical, since it is coupled to a diesel engine causing far higher vibration levels. Secondly, it is not connected to the propeller shaft, and therefore structural-borne vibrations originating from the generator will not radiate into the surrounding water very well.

SBN levels were measured at various operating points for the propulsion motor (PMM 1000), and full-load results are presented in the graphs. As can be seen from Figure 5, levels are below the mobility-corrected DNV-GL Silent F criteria

Figure 4: SBN levels for a PMM 1000 propulsion motor at full load. X=axial Y=horizontal and Z=vertical direction. DNV-GL Silent F limits were used as criteria, and corrected with the measured mobility of the test bench

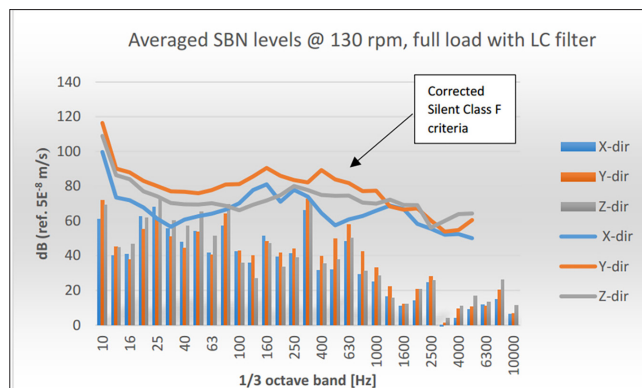
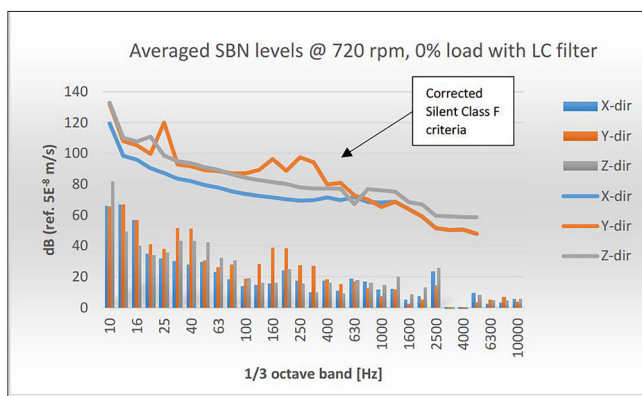


Figure 5: SBN levels for a PMM 630 generator at no-load. X=axial Y=horizontal and Z=vertical direction. DNV-GL Silent F limits were applied as above



throughout the range, except slightly at the 25Hz frequency band in the axial direction. It was found that this was caused mainly by resonance between the two machines, the motor and braking generator, which were mechanically coupled through a stiff coupling. It must also be pointed out that, during the measurement, there were two machines, the tested motor and the braking generator, operating at full load on the same mechanical platform. This naturally increases SBN levels compared to a real situation, where only a single machine is connected per propeller.

Resilient mountings were applied in the measurements for both the generator and motor, as they both play a crucial role in achieving low SBN levels. Besides measuring SBN levels at various load points, the effect of frequency converter output filtering was verified by measuring with and without the filter. By applying LC-type machine-side filtering, high-frequency SBN levels were drastically reduced.

In addition to proper electromagnetic design and use of resilient mountings, the use of filtering on the motor/generator output seems to be one of the most effective ways to reduce SBN levels. After analysing

the SBN levels of the propulsion motor, it seems likely that those levels can be further reduced from the values shown here by using resilient mountings with more flexibility.

Conclusions

Measurements presented here prove that 'silent' vessels can be designed and built using PM machines. In the past, DC motors were required, but they are physically big and heavy. They have very complex mechanical construction, causing issues with reliability and need for constant maintenance, along with having rather low efficiency.

Some of these drawbacks have been solved using either electrically excited synchronous or induction motors, but both these machine types have their own drawbacks – mainly physically large size and lower efficiency.

PM machines are very simple mechanically, therefore are reliable and need minimal maintenance, plus they run at very high efficiency due to lack of rotor winding. Proper electromechanical design, combined with the use of resilient mountings and converter-side filtering, results in very low structural-borne noise levels, which can meet even the most stringent DNV GL Silent F requirements. **NA**