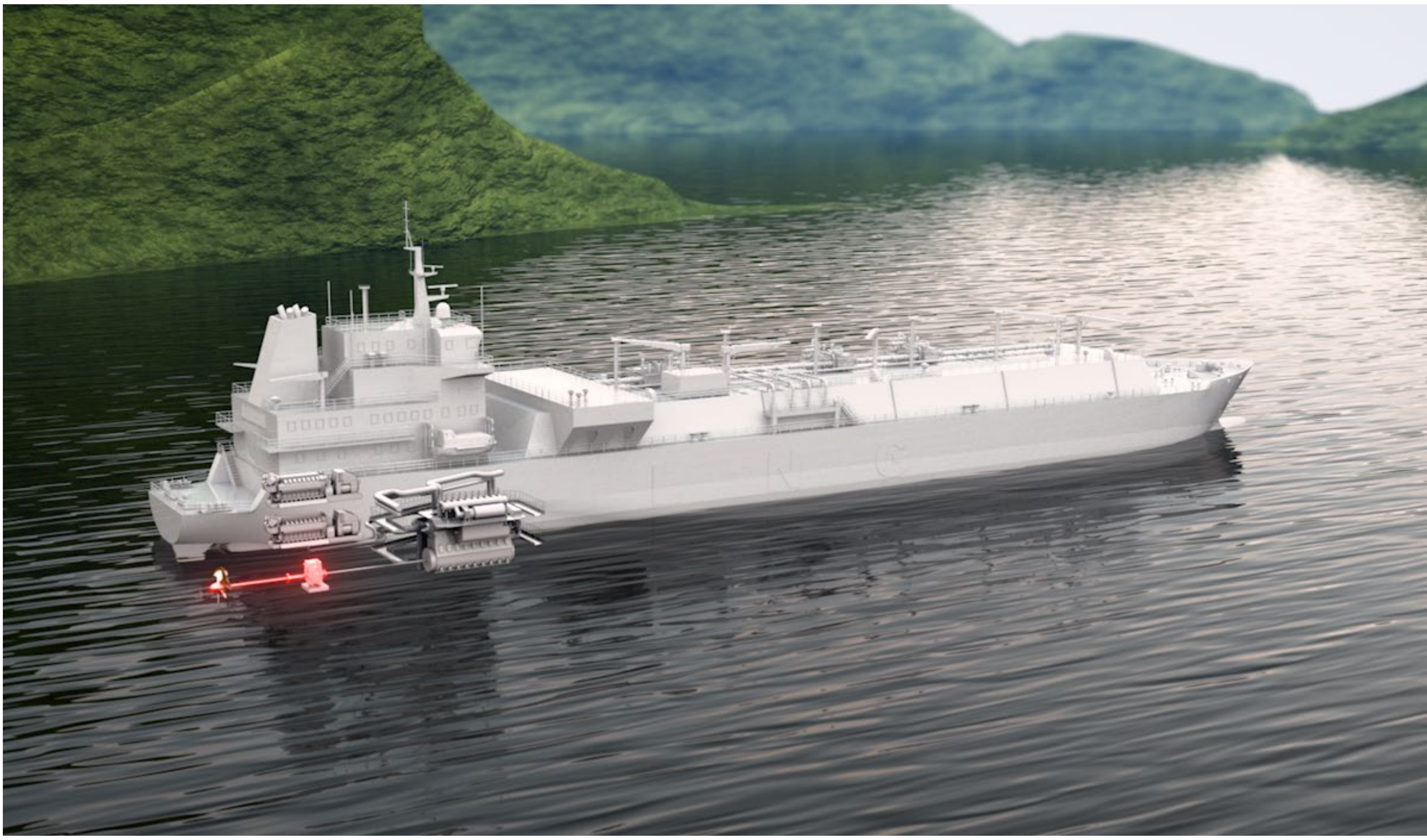
WHITE PAPER

Verifying the energy efficiency of ABB permanent magnet shaft generators

How testing and modeling are used to determine efficiency with a high degree of accuracy



This paper focuses on the efficiency of PM shaft generators, and explores how their efficiency can be tested and verified. It describes different efficiency testing methods and explains how ABB has created models that are digital twins of the machines' electrical design. These models enable the efficiency of PM motors and generators to be determined accurately. In addition to PM shaft generators for marine vessels, the paper incorporates experience acquired from ABB's PM motors in Azipod® propulsion units and PM wind power generators.

Table of contents

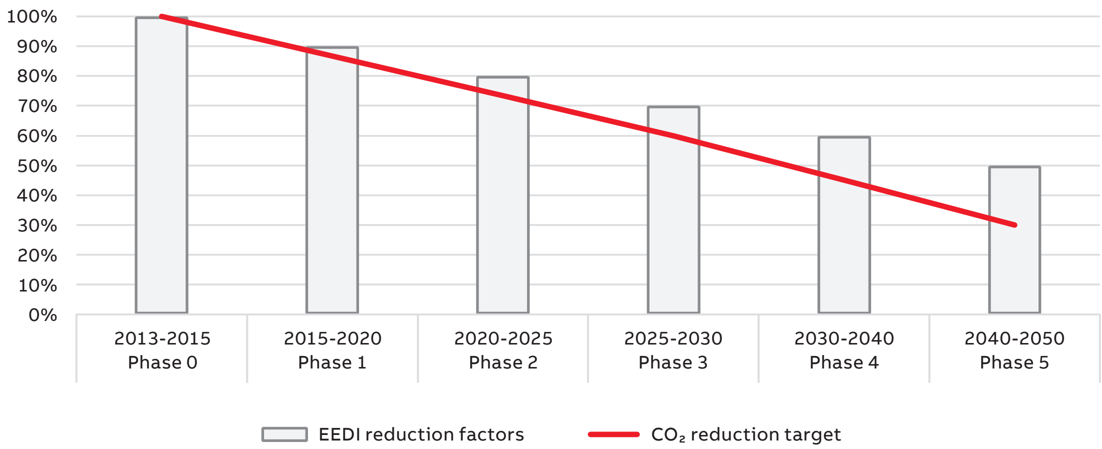
Introduction

As the world urgently seeks ways to reduce carbon emissions, the International Maritime Organization (IMO) has set the objective of cutting total annual greenhouse gas (GHG) emissions attributable to international shipping by at least 50% by 2050 (compared to the 2008 level) [1]. The requirements are tightened every five years in order to promote continued technical development and help the industry reach the target.

Some countries and regions are looking to accelerate this process. The EU, for example, aims for Europe to be the world's first climate-neutral continent by 2050, and is bringing shipping into the EU Emissions Trading System (ETS) [2].

—

Chart 1. IMO Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) reduction targets [1]

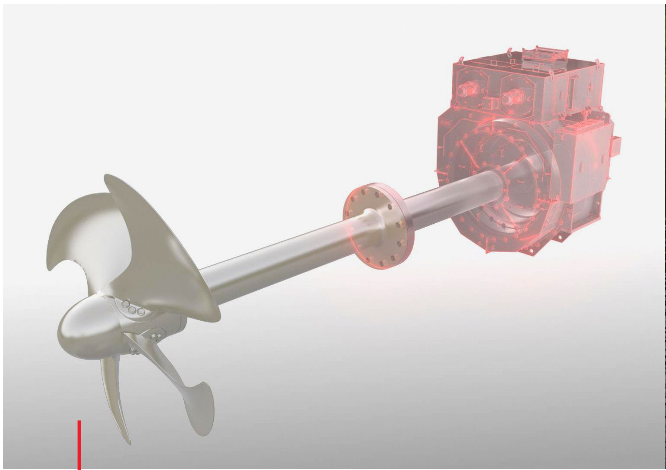


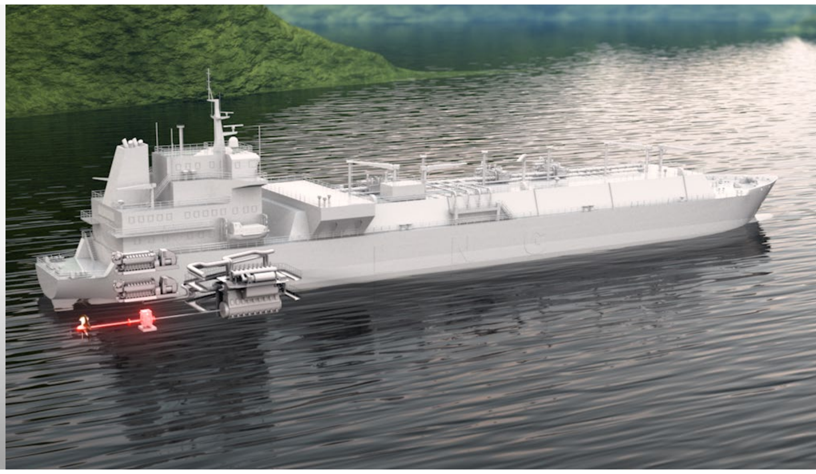
- 2022: EEDI Phase 3 enters into effect for certain ship types with up to 50% carbon intensity reduction
- 2023: CII measures enter into effect, and it becomes mandatory for all existing ships to calculate their Energy Efficiency Existing Ship Index (EEXI)

Efficient permanent magnet (PM) shaft generators deliver significant reductions in fuel consumption and emissions, and therefore help ship owners and operators meet emissions requirements while reducing fuel costs. They offer high power density in a compact size and are efficient at both full and partial loads. The efficiency benefits are maximized by utilizing a variable speed drive (VSD) to enable the propulsion system to run in its optimal operating area.

This paper focuses on the efficiency of PM shaft generators, and explores how their efficiency can be tested and verified. It describes different efficiency testing methods and explains how ABB has created models that are digital twins of the machines' electrical design. These models enable the efficiency of PM motors and generators to be determined accurately. In addition to PM shaft generators for marine vessels, the paper incorporates experience acquired from ABB's PM motors in Azipod® propulsion units and PM wind power generators.

PM shaft generators provide many other important benefits, including improved performance, reduced CAPEX and OPEX, improved reliability and safety, and fast and easy installation. These benefits are presented in detail in an ABB white paper [3].





Permanent magnet technology enhances efficiency, performance and reliability of vessels

Cuts CO_2 emissions by several tons per day

20% smaller, 30% lighter than conventional generators

Background and history

The technology behind ABB's PM shaft generators – PM rotors and reliable stator insulation systems – has already been used in numerous solutions: PM rotors in hundreds of marine propulsion motors and offshore wind turbines, and stator insulation systems in thousands of marine generators and propulsion applications. These solutions' cumulative operating time to date already exceeds 4,000 years, underlining their high reliability and safety in marine and offshore environments.

Proven facts about **ABB large permanent magnet machines**

1200+
ABB MW class permanent magnet machines installed around the globe

4000+
Accumulated years of successful operation by ABB large (over 200 kNm torque) permanent magnet machines

200+
ABB permanent magnet machines delivered for marine applications

30+ years
Of ABB permanent magnet technology

Patents
Technology leadership in permanent magnet portfolio with tens of patents

Global network
ABB Service facilities worldwide

24/7
ABB service and support/hotline

—
ABB's reliable PM technology is used in Azipod® propulsion units in the power range 1-15 MW.

—
ABB high efficiency in-line shaft generators are available in the power range 0.5-5 MW. They help vessel owners and operators reduce fuel consumption and meet emissions requirements.

Major improvements in energy efficiency

It is generally more efficient to produce onboard power using a shaft generator driven by the main propulsion engine rather than running the auxiliary gensets. This is because in most cases the main engine is more efficient than the smaller engines that drive the gensets. Operating the shaft generator is an effective use of the main engine's power reserve.

Efficiency is further boosted by utilizing a generator based on PM technology instead of a conventional induction or synchronous generator – in shaft generator applications PM generators are more efficient at all power levels. Compared to induction and electrically excited synchronous generators, PM generators have minimal losses in the rotor and lower winding losses in the stator. ABB PM shaft generators are engineered to operate at high efficiency within their typical loading area.

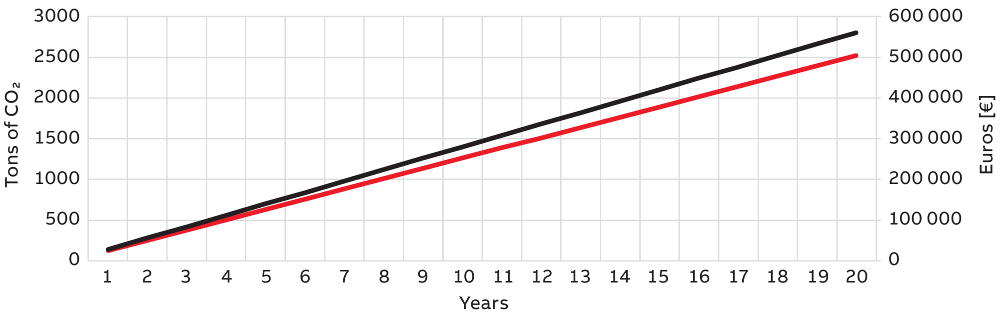
A PM shaft generator usually cuts fuel costs by 3–4% with the vessel's engine operating at full load. By running the engine at its highest efficiency operating point the reduction in fuel costs can reach 10%.

Higher efficiency saves energy and reduces emissions
(comparing the performance of PM and induction shaft generators)

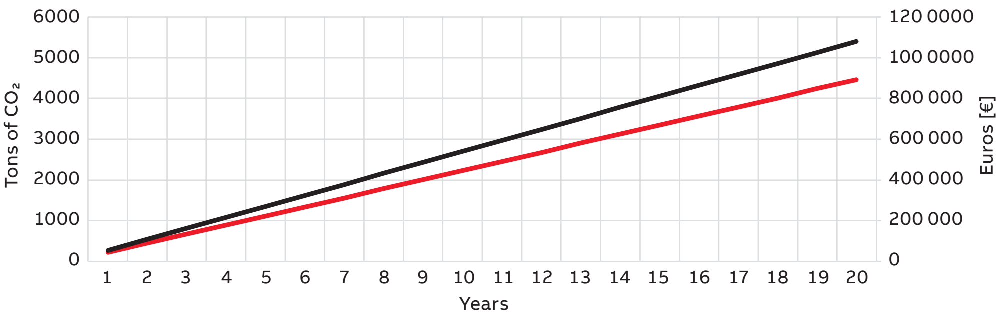
Rated output	1.5 MW	3 MW
Efficiency ratings		
Permanent magnet shaft generator	97 %	98 %
Induction shaft generator	93 %	94 %
Assumptions (based on LNG fuel)		
Energy cost [$/kWh]	0.1	0.1
CO_2 emissions [g/kWh]	413	413
Life time [years]	20	20
Annual running hours [h] (70%)	6000	6000
Average operation rating [% of Pn]	75 %	75 %
Discount rate	4 %	4 %
Savings with PM generator compared to induction		
Life cycle energy savings [$] *)	562 000	1 080 000
Annual energy savings [$] *)	28 000	54 000
Annual CO_2 emissions savings [tons]	126	223

*) Excluding CO_2 emission fees

Benefits of premium efficiency permanent magnet shaft generator (1.5 MW)



Benefits of premium efficiency permanent magnet shaft generator (3 MW)



Emission savings, CO_2 [tons]

Energy savings [€]

Saving fuel means cutting emissions, and this helps vessels meet current and future environmental regulations, including the IMO's requirements as defined in the EEDI and EEXI.

The considerable fuel savings made possible by variable speed operation mean big reductions in carbon dioxide (CO_2) and nitrogen oxide (NOx) emissions.

Variable speed operation maximizes efficiency

The need to deliver a fixed frequency to the onboard grid previously meant that shaft generators had to be driven at a constant speed – i.e. the main engine had to run at constant speed. Vessels spend a lot of their operating time at partial loads, however, and the engine and propeller are less efficient when operating at low loads with a high speed.

These issues are avoided by installing a variable speed drive (VSD), which allows the most efficient combination of speed and propeller pitch to be utilized. By enabling the main engine to be run at a more favorable operating point, the variable speed drive unlocks significant fuel savings. ABB supplies PM shaft generator and VSD packages which are perfectly matched for optimal performance.

The shaft generator is optimized according to the vessel's main engine speed and power. The average loading of the shaft generator in variable speed operation is typically 50-75%. The system is generally dimensioned so that the shaft generator PTO (Power Take Off) is roughly 10-20% of the main engine power. Variable speed operation is optimized in such a way that SFOC (specific fuel oil consumption) is minimized – i.e. the system is designed so that it operates in the engine's optimal operating area for most of the time.

As Chart 3 shows, reducing the propeller speed typically means that less total power is required to achieve the same vessel speed. Furthermore, as can be seen in Chart 4, reducing engine speed can often lead to a better specific fuel consumption due to a more optimal operating point.

Chart 3. Propeller power demand

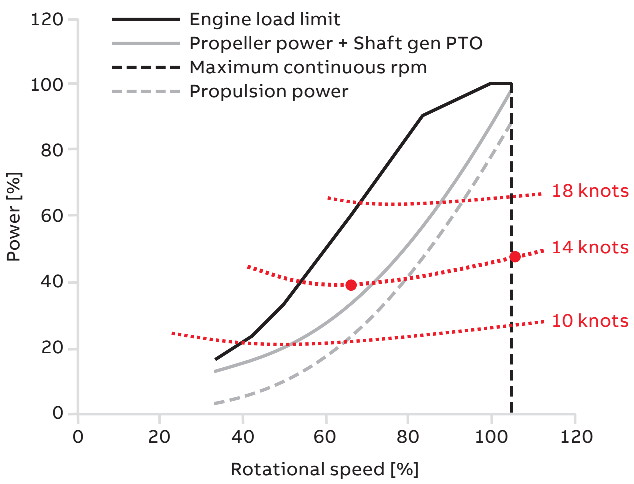


Chart 4. Engine specific fuel oil consumption

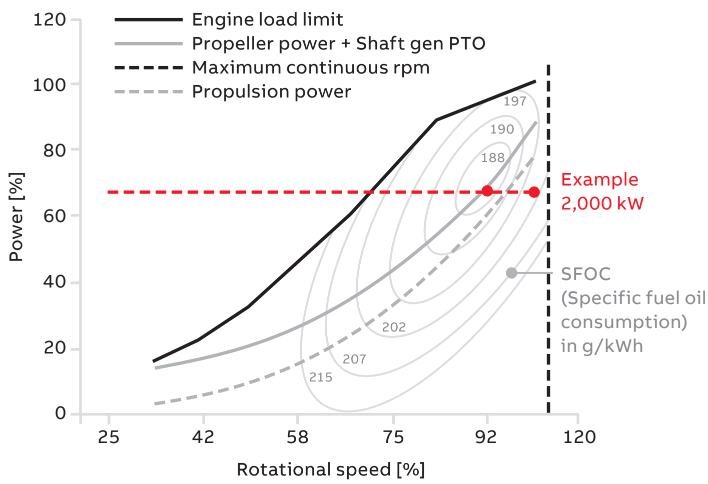
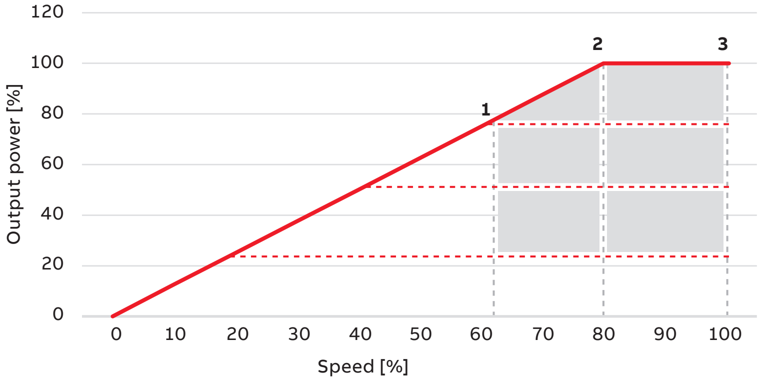


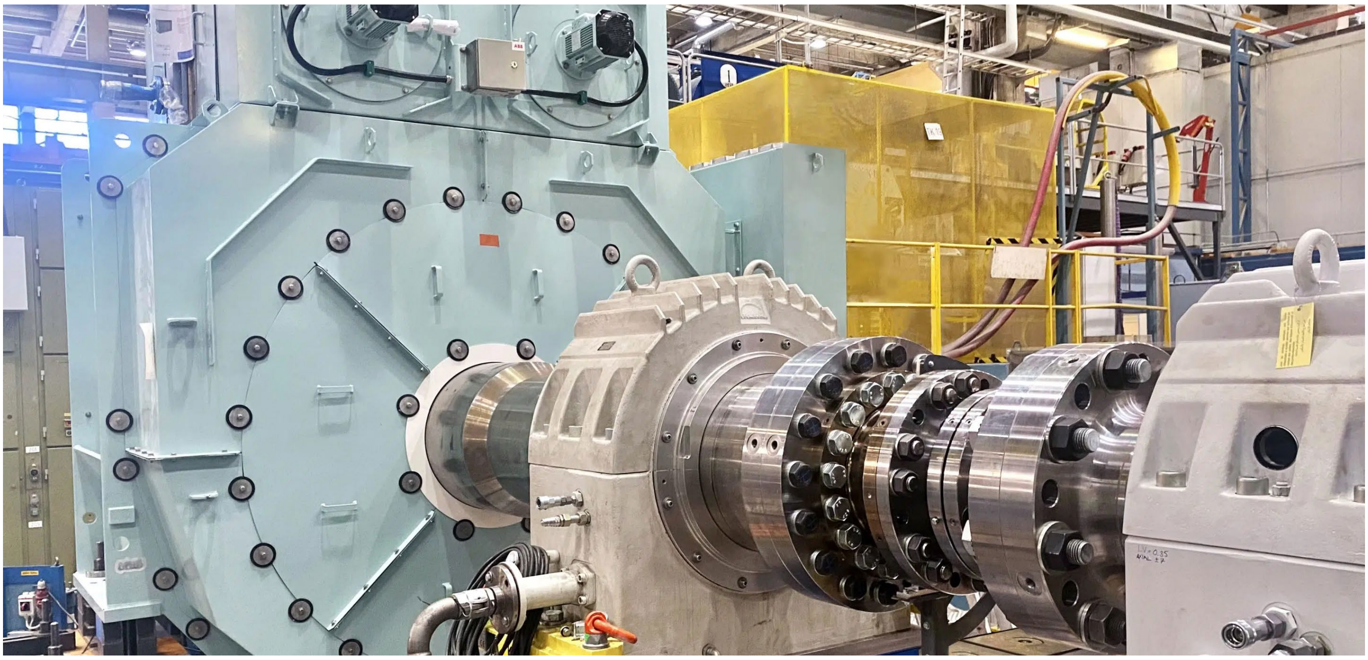
Chart 5. Typical shaft generator power/speed curve



1 Minimum speed
2 Base (rated) speed (the lowest speed at which power is 100%)
3 Maximum speed

Typical shaft generator operation area (defined by the engine's load limit)
The typical average loading area is 50-75%

Ensuring high performance and efficiency



—
PM shaft generator undergoing back-to-back testing at ABB's test facility.

Electrical machines for vessels – like PM shaft generators – are always type tested, and they are also certified by the marine classification societies. In general the first product in each series is subjected to type testing. The role of third-party certification bodies in type testing is to perform surveillance and approval. Design and basic testing requirements are specified in IEC Standard 60034, as well as in marine classification requirements.

Type testing usually involves reactive load tests, which means that the generator and variable speed drive are tested together without an active load. The type test program validates the basic performance and quality of the generator series. The type testing standards do not require efficiency measurements for PM shaft generators in cases where a load machine is not available. Because ABB focuses on energy efficiency, it has performed full active load testing to validate loss calculation models for its PM shaft generators.

Back-to-back full-load testing

Back-to-back full-load testing is available to validate the efficiency of shaft generators. To conduct the tests, two PM shaft generators are connected back-to-back. One of the units is operated as a motor and the other as a generator. Back-to-back testing naturally requires the availability of two identical shaft generators.

Two methods are available to measure efficiency during back-to-back testing:

- Direct ('mechanical') method – a torque transducer is mounted on the shaft between the motor and generator to measure the torque supplied by the motor. The electrical output from the generator is recorded, enabling losses and therefore efficiency to be calculated.
- Dual supply ('electrical') method – the electrical input to the motor and output from the generator are both measured, enabling losses and efficiency to be calculated.

The dual supply method is less accurate than the direct method, due to the averaging process and the higher losses in the motor. This paper will focus on results obtained using the direct method, but ABB has utilized – and evaluated the accuracy of – both methods.

Note that the testing methods specified in the IEC standard allow a tolerance of 15% for actual measured losses, which is relatively wide. For example, when a generator's data sheet shows an efficiency level based on a theoretical loss figure of X kW, actual losses measured during testing can be up to X +15% without requiring any revision of the efficiency figure. ABB's objective is to achieve high efficiency, and to state efficiency levels with a high level of accuracy, and therefore ABB always aims for results that are better than the IEC's permitted tolerances.

Efficiency calculation models

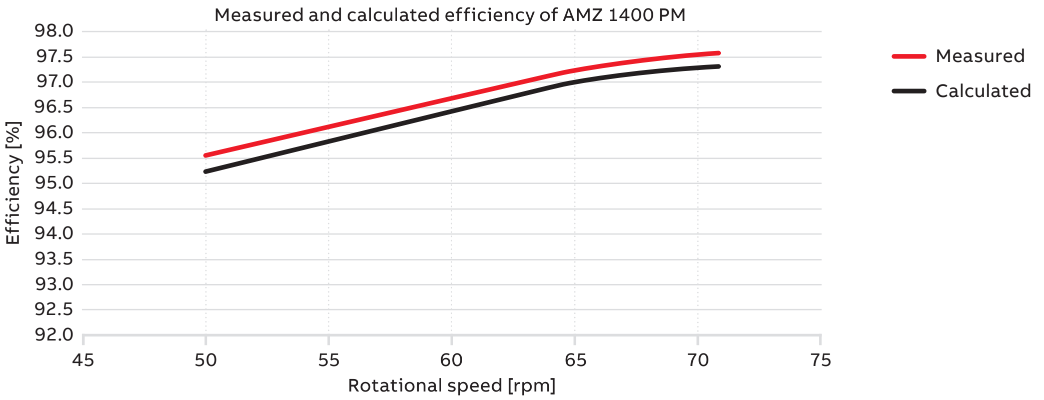
ABB has created advanced models that calculate the efficiency of PM motors and generators with high precision. The models include segregated losses, i.e. separate loss components in the generator, as well as additional losses induced by the variable speed drive. The models are based on work undertaken over several decades to develop PM technology, and on the design tools utilized in this work. These development efforts have included extensive load testing, which has provided a basis for calibrating and validating the models. The same basic principles and models are used to calculate the efficiency of the PM motors used in Azipod® propulsion units.

—

Chart 6. Example of measured and calculated efficiency as a function of rotor speed (before final calibration of loss model)

—

Measured and calculated efficiency curves. The calculated efficiency curve is based on output from the loss model prior to final calibration. Testing was performed on the pilot machine for a generator family, operating at 100% load.



Even though Chart 6 is based on output from the loss model before it had been finally calibrated, it clearly shows that the calculated efficiency levels closely follow the measured results. The models are conservative, and the preliminary calculated values tend to be lower than the measured values.

Charts 6 and 7 demonstrate that ABB's models predict efficiency levels very accurately, and the results are sufficiently precise for most purposes. As models for the different generator types have been rigorously validated, customers can rely on the values shown in the technical specifications. Given that the first two PM shaft generators in every series are very thoroughly type tested and undergo marine certification, whereby ABB measures efficiency in back-to-back testing, ABB considers that it is not necessary to undertake back-to-back testing on later products in the same product series to confirm their efficiency.

Back-to-back testing is, however, available on request for customers who require efficiency measurement for their generators, as well as for customers who need 'string' tests performed with their project's actual components.

In the case of large generators, the arrangements necessary to perform back-to-back testing for efficiency measurements – including organizing availability of two identical generators, specialized personnel and equipment – naturally take time, and customers who choose not to have this testing performed benefit from shorter overall delivery times.

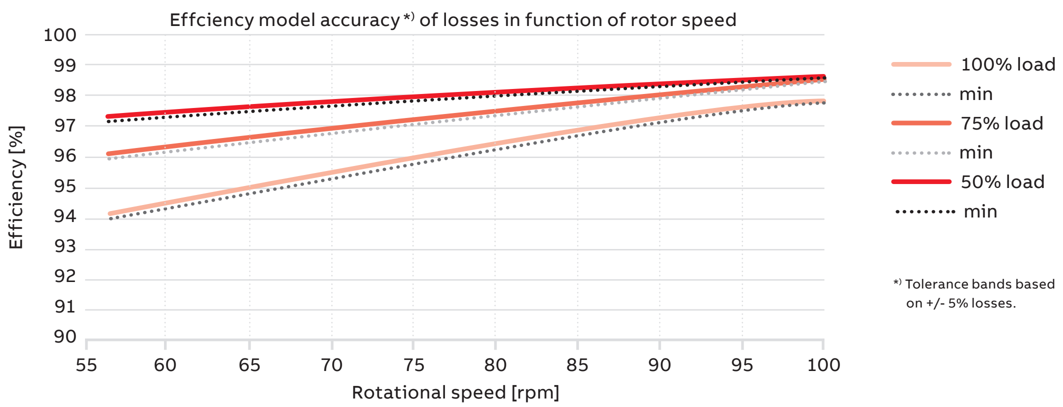
It is important to point out that choosing to rely on the calculated results rather than having back-to-back testing done on each project does not compromise the quality validation of the original type test.

—

Chart 7. Calculated efficiency as a function of rotor speed (loss model fully calibrated)

—

Calculated efficiency curves with a minimum tolerance of 5% of losses. These curves are based on output from the loss model following calibration and validation. It can be stated with a high degree of confidence that measured efficiency values will lie within the tolerance bands.



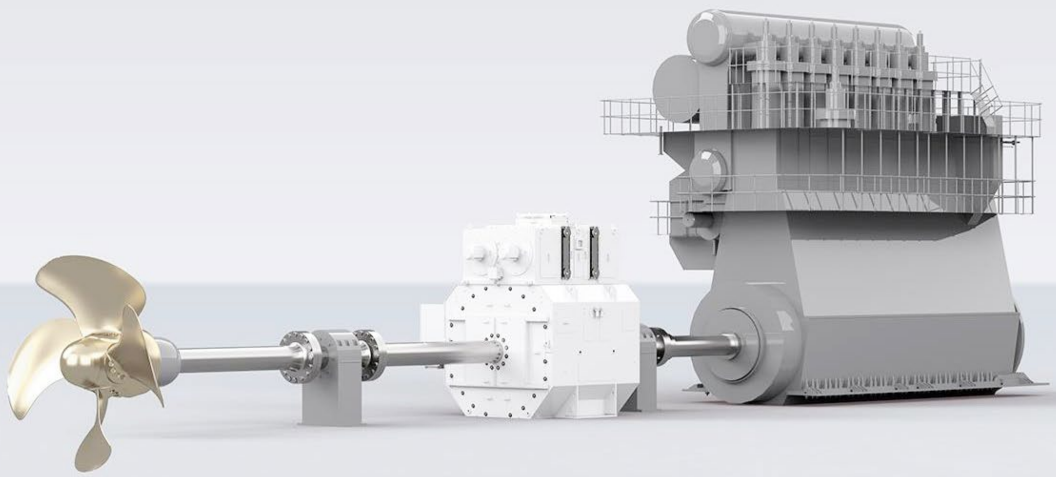
Conclusion

ABB's sophisticated models determine the efficiency of PM motors and generators with high confidence. The models are validated by measurements taken during active load testing. Combined with decades of development experience, the models are extremely accurate.

ABB's design tools, where digital twins of the drive and generator are coupled together, enable the optimization of the variable speed drive and generator package.

Based on the validated models, normal type tests are sufficient in most cases and back-to-back testing is only really necessary in special cases, for example if major changes have been made to the generator, or a project-specific variable speed drive has to be tested with the generator.

As a consequence, ABB considers that it is not necessary to perform back-to-back testing to measure efficiency for every project. However, these tests are optionally available for those customers who need them.



References and further information

[1]
IMO: Improving the energy efficiency of ships
https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx

[2]
European Commission / Climate Action: Reducing emissions from the shipping sector
https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en

[3]
ABB white paper: Towards an energy efficient future for shipping/
High efficiency ABB permanent magnet shaft generator solutions
https://search.abb.com/library/Download.aspx?DocumentID=9AKK108466A6782&LanguageCode=en&DocumentPartId=&Action=Launch

—
For more information, please contact
your local ABB representative or visit

new.abb.com/motors-generators

Additional information
We reserve the right to make technical changes or modify the contents of this document without prior notice. With regard to purchase orders, the agreed particulars shall prevail. ABB does not accept any responsibility whatsoever for potential errors or possible lack of information in this document.

We reserve all rights in this document and in the subject matter and illustrations contained therein. Any reproduction, disclosure to third parties or utilization of its contents – in whole or in parts – is forbidden without prior written consent of ABB.

© Copyright 2023 ABB. All rights reserved.
Specifications subject to change without notice.

9AAU000000000069 REV A 27.11.2023