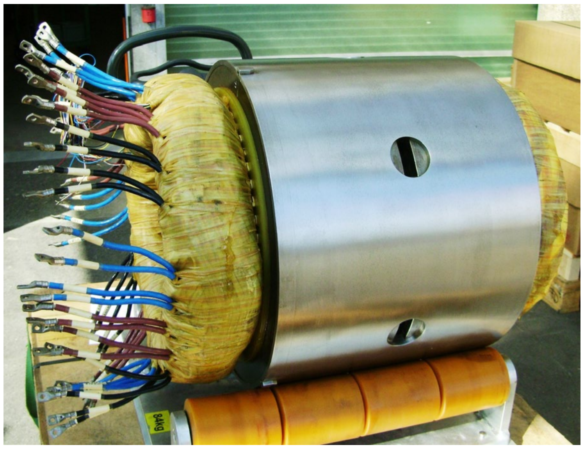
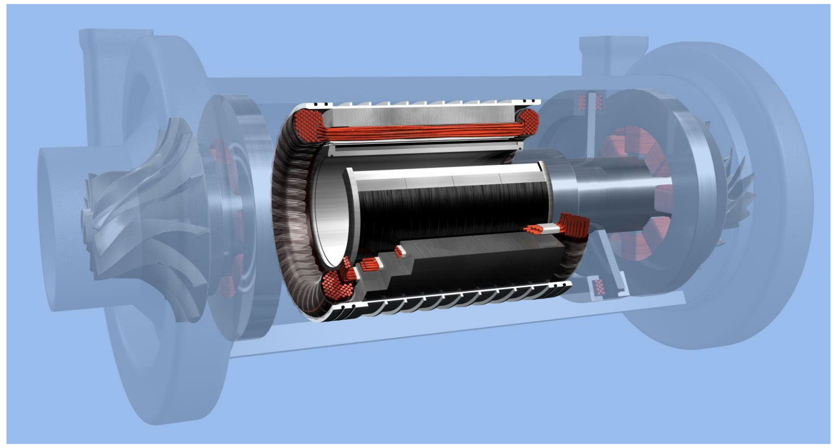
High-Speed Generators for Turbomachinery

Rotors & Stators for Integration into Permanent Magnet Machines for High Performance Applications

Elektromaschinen und Antriebe



1.6MW, 25K RPM Stator for Shipboard Power Generation



Conceptual Drawing of e+a Rotor & Stator w/Cooling Jacket Embedded in a 2-stage Turbocharger with Magnetic Bearings

High-Speed Generators

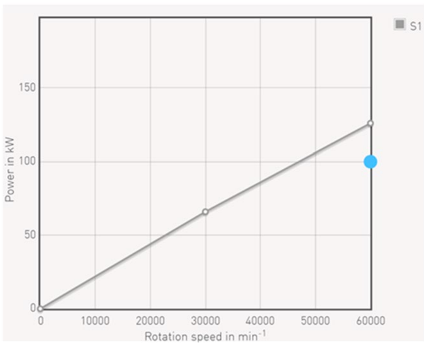
This document gives a short overview of machines used as high-speed generators in applications like micro-turbines, energy recovery, portable power sources, generators for Organic Rankin Cycle (ORC) systems, range-extenders attached to gas turbine engines (GTE) for vehicle applications, and high-speed generators replacing gear boxes for direct drive generation of energy from a gas turbine engine through a flexible coupling. These generators are produced by e+a in Switzerland and are primarily "low voltage" (<1000V), Permanent Magnet machines, and range in power from a few KW at 500K RPM to 1.6MW at 25K RPM. All e+a generators can be used as high-speed motors as well, even as both in the same application (e.g. used as a motor to start a gas turbine engine, then switch to generator mode when the gas turbine fires up and approaches operating speed). e+a supplies the electromagnetics (rotors and stators) for "embedded systems", see picture above right. The customer supplies the shaft, bearings, housing, cooling and Variable Frequency Drive (VFD).

Introduction

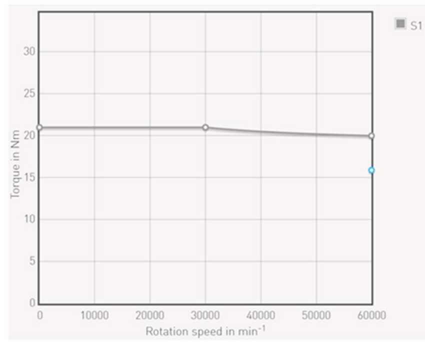
There is a growing demand for high speed generators based on an evolving need for increased power density, lower cost and smaller size provided by high-speed systems; compared to low speed (50/60 Hz) generators driven through a gearbox that are bulky, less efficient and require a separate oil system to lubricate gears. These attributes of high-speed machines stem from the quasi-linear relationship between rotational speed and shaft power of an electrical machine while providing a constant torque (see graphics below). Increasing the rated speed of a machine is an effective way to boost power density and efficiency, allowing this approach to take advantage of increased shaft power without changing the size of the machine. In addition, the same performance can be provided in a much smaller volume when using a high-speed device as opposed to a standard 50/60 Hz generator. In high-speed applications the concept is to directly apply an energy conversion unit (generator) to a mechanical system rotating at high speed. Directly driven generator elements (stators and rotors with Permanent Magnets wrapped in carbon fiber or steel sleeves) replace a large standard motor/generator (50/60Hz), a gear box and an external oil system. While efficiency is increased, the space required for the application is significantly reduced, and the logistics footprint is lowered, producing savings on long term maintenance costs.

With these significant improvements energy recovery systems, for example, become much more interesting from a financial and ecological perspective, while the ability to supply basic energy in a wide variety of powers is enhanced because the sizes of the systems are smaller and more compact, and logistic and repair costs are reduced. So high-speed motor elements are a significant step forward in the ongoing development of green and efficient energy applications.

Power, kW



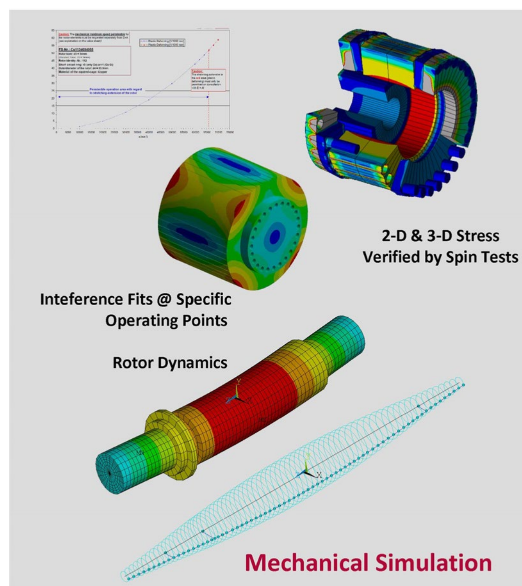
Torque, Nm



Power vs. Speed & Torque vs. Speed Charts for an e+a Constant Torque, PM Generator

Inside the Generator

The generator elements need to be held to close mechanical, electrical and quality tolerances due to the high rotational speeds and significant centrifugal forces acting on the rotor, in addition to the high heat experienced by the stator windings and laminations, exposing materials to heightened mechanical stresses close to the edge of their endurance. To ensure system reliability and a long service life these high-speed elements need to undergo extensive simulations for mechanical stress, thermal energy dissipation, structural mechanics, rotor-dynamics and electromagnetic performance. interaction between the high-speed inverter and generator also needs to be quantified because the details of the inverter's construction (active or passive front end, dual or multi-level switching, possible requirements for a sine filter between the generator and inverter) have a significant impact on heating, noise, cogging and efficiency of the generator.

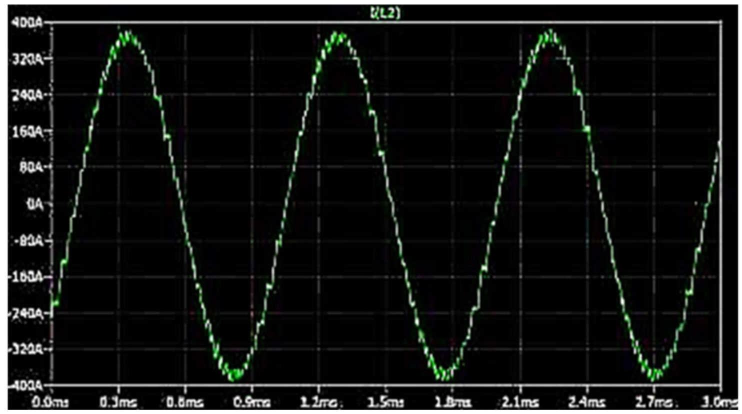


e+a Employs Mechanical, Electrical, Electro-Magnetic and Rotor-Dynamic Simulation Tools for Generator Design

Stators made by e+a are identical for both induction and permanent magnet systems, and have different end winding treatments depending on the cooling scheme of the system that the elements are embedded in (air cooling for smaller systems, water or other liquid cooling using a cooling jacket around the stator, or refrigerant cooling blown over the bare end windings and through the air gap between the rotor and stator like in HVAC applications). The size of the air gap is of particular interest because it affects cooling ability, magnetic flux density in the stator, and windage losses caused by turbulent flow in the gap itself.

Rotors in e+a Permanent Magnet generator systems are typically steel carriers with attached magnets that are retained by a carbon fiber sleeve. Optionally a steel sleeve can be used for higher/lower temperature applications or with lower speed requirements. Steel sleeves, for example, are used on pumps with e+a motors that are immersed in cryogenic fluids. Quality Control, testing and traceability requirements on carbon fiber sleeves are quite strict and e+a has a simple mechanical scheme that allows a shaft to be inserted into a PM rotor without using heat (which might demagnetize the permanent magnets). Seven years' worth of destructive testing (using more than 500 rotors) were performed on various carbon fiber types and resin formulas to produce the high quality, highly reliable rotors for PM systems that e+a has today.

Inverter



Simulated Ripple Current in a 2-Level Inverter:
Source Oztek Corp.

Conventional variable speed drives rely on motor/generator inductance to filter the inverter's switching waveform to produce a relatively smooth motor current. The remaining switching current through the generator is referred to as "ripple current", since it appears as a triangular signal that ripples through the fundamental waveform. The simulated motor current waveform, shown on the right, has approximately three percent current ripple. This ripple current causes high frequency magnetic flux, which in turn, causes losses in a motor/generator by creating eddy currents in the rotor, in permanent magnets attached to the rotor, and in the stator. None of the ripple current in a Variable Speed Drive or Inverter waveform produces torque; it all ultimately goes to producing losses in the form of heat in the rotor and stator. To maintain acceptable rotor losses for a particular system, and especially in applications involving permanent magnet motor/generators, motor manufacturers require low ripple current, and specify a "sine filter" to be placed between the inverter and motor to provide further ripple current reduction. The cutoff frequency of this filter must be placed sufficiently above the generator's fundamental frequency to avoid excessive drive losses, but also sufficiently below the drive's switching frequency to effectively reduce the ripple current. The use of a sine filter between the motor/generator and a typical two-level inverter causes filter insertion loss and filter power loss, as well as the increased cost and bulk of the filter. The insertion loss reduces the voltage available to the motor/generator requiring a lower torque constant winding and therefore a higher current inverter for a given motor/generator power level. In addition to sine filter inductor losses, resistors are needed to damp resonance. The power loss in these elements can be significant and the effect is to reduce two-level inverter efficiency in many systems by several percent.

Since much of the drive's loss is directly related to switching frequency, some controllers employ an advanced power stage topology, called a Multi-Level Inverter (MLI), which has fewer switching losses and lower filtering requirements than conventional two-level inverters. Each time a switch changes state, there is an energy loss related to the change in voltage level. That change level for a three-level MLI is one-half the amount of that of a two-level inverter, which results in approximately 50 percent less switching loss. Additionally, the 50 percent reduction in switching voltage level also reduces the filtering requirement by 50 percent. Using a MLI inverter typically negates the need for an external sine filter, with its accompanied bulk, expense and efficiency loss.

Generator Projects

An overview of recent generator projects at e+a:

Power (KW)	Speed (RPM)	Application
1.3	500,000	Man Portable Generator
8	180,000	Airborne UAV
35	90,000	Portable Generator
80	95,000	Automotive Range Extender
140	64,000	GTE Generator, Foil Bearings
350	75,000	Truck Range Extender
1,200	31,000	Energy Generation
1,600	25,000	Shipboard Power Generator

e+a Elecktromaschinen und Antriebe AG
Bachstrasse 10, 4313 Möhlin,
Schweiz/Switzerland
T +41 (0)61 855 92 92 F +41 (0)61 855 92 99
info@eunda.ch
https://motorscout.eunda.ch
www.eunda.ch

Mike Drumm
ExSell Motors
Domestic & International
Concord, CA
T (925) 685-0227
mdrumm@eandaUSA.com
www.eandaUSA.com