More Power to You

Simulation helps Indar to design one of the world's highest-efficiency permanent magnet wind turbine generators.

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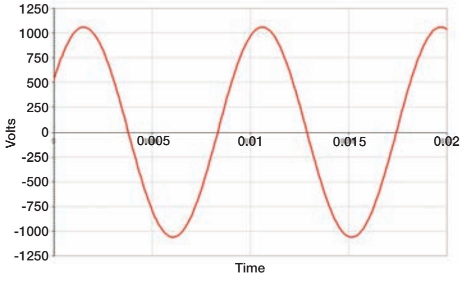
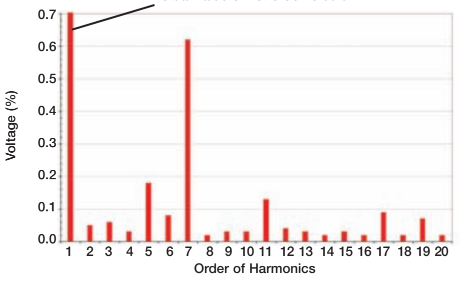
Indar high-speed permanent magnet generator with air–water cooling option

Wind power is the world's fastest-growing energy source, with 37.5 gigawatts of installed capacity added in 2009. The Global Wind Energy Council expects this resource to grow by 160 percent over the five-year period ending 2014. One rising trend is permanent magnet generators (PMGs), as they offer higher efficiency and design flexibility. Indar Electric, S.L., set out to develop a 2.5 MW PMG for wind power applications with the ambitious target of achieving an unprecedented 97.7 percent level of efficiency at rated load in converting mechanical to electrical energy using a permanent magnet generator. Another goal was to increase performance and efficiency at partial loads, because wind turbines often run at partial load. Traditional build-and-test methods could not achieve these goals in a reasonable amount of time. Thus, Indar applied electromagnetic field and fluid flow simulation to facilitate the process.

Indar Electric was founded in 1940 as a manufacturer of small electric motors. In 1997, it became part of Ingeteam, a Spanish renewable energy company that currently holds about a 15 percent global market share for wind power components. Indar produces a wide range of generator concepts, including more-traditional double-fed induction generators (DFIG) and newer PMGs. PMGs generally offer higher efficiency at rated load and even more at partial loads, since the permanent magnets eliminate the need for rotor windings that, in turn, remove rotor ohmic losses. PMGs also eliminate the need for brushes, which reduces possible problems and maintenance needs.

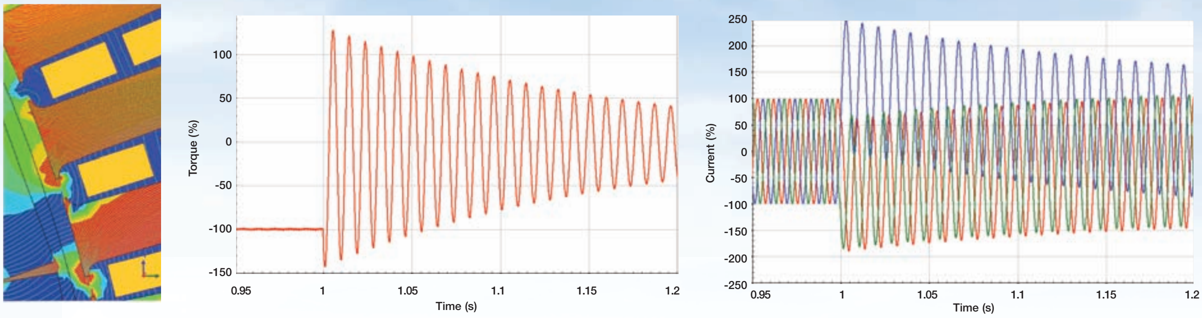
The Indar design team faced several major challenges in developing its newest PMG. Achieving high efficiency was the overarching goal, but there were a number of other targets that had to be simultaneously achieved for reliable operation. Cogging torque, caused by the interaction between the rotor's permanent magnets and the slots on the stator core, had to be reduced to 0.1 percent of overall torque. Voltage harmonics (THD) in the output had to be kept below 0.5 percent. For the cooling system, a demanding goal was set to maintain magnet temperature below 100 C to assure good performance of the magnets over a 20-year lifetime.





Magnetic flux density level in the stator (left) identifies areas of high losses. The generated voltage (upper right) and fast Fourier transform (FFT) (lower right) results for a no-load condition are also shown.

Indar engineers used Maxwell low-frequency electromagnetic field simulation software from ANSYS to evaluate the effect of different geometries and magnet properties on the electromagnetic performance of the generator. Well-known basic equations were used to develop a preliminary generator design.

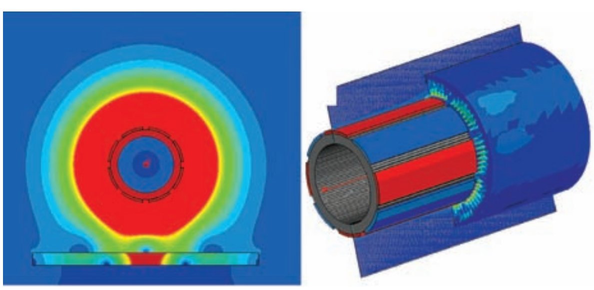


Magnet behavior in a three-phase short circuit as predicted by Maxwell

Engineers first created a 2-D and, later, a 3-D model of the generator, relying primarily on manufacturing drawings to reproduce the geometry and material properties of rotor and stator laminations and coils. The time step of the simulation was adjusted to match the rotating speed of the generator and the number of poles in the permanent magnet. Engineers simulated the performance of the proposed design under no-load, full-load and short-circuit conditions.

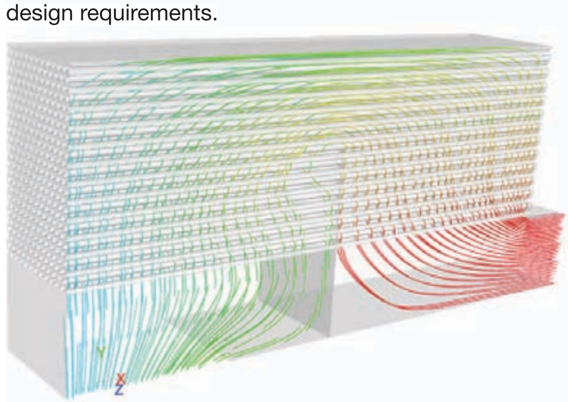
The results of the simulation included the voltage wave form produced by the generator, a measurement that was compared to the design requirement so that harmonic levels could be evaluated. The voltage fast Fourier transform output capability in Maxwell provides the voltage at different frequencies, making it straightforward to calculate the harmonic levels for a particular design.

The behavior of the design in the event of a short circuit was another important consideration. Short circuits may be caused by mechanical failure in the generator, insulation breakdown or power converter malfunction. Engineers studied the magnetic field generated in each area of the permanent magnet in a short circuit, expecting to ensure that the magnet had the right properties to avoid any damage. Generally when designing a PMG, Indar engineers consider a wide range of factors, including the contribution of magnet temperature, rotational speed, switching frequency and short-circuit (two-phase and three-phase) performance to achieve ideal magnet behavior for the entire lifetime of the generator circuit.



Electromagnetic simulation of the balancing operation and inserting the rotor in the stator with a crane

In the full-load simulation, engineers looked at the input required by Ingeteam frequency converters for the available switching frequencies to achieve nominal torque, high current and low losses. The team examined induction levels in the stator because of their important effect on efficiency. Though high induction levels make it possible to reduce the size of the generator, they also increase iron losses. Maxwell results showed the distribution of losses over the geometry of the stator, providing guidance for design changes to improve efficiency. Indar engineers continually modified the design, attempting to reduce losses in the stator copper, mechanical losses, and losses created due to switching frequency when working with frequency converters — all while achieving the other design requirements.



Flow speed and temperatures through the tubes in the air–air cooling system

Because of the magnet field's high strength even when the PMG is not rotating, Indar engineers simulated the process of assembling and balancing the rotor, ensuring it could be safely accomplished. They determined the level of magnetic forces generated while inserting the rotor, which made it possible to specify assembly tools that could withstand these forces. The generator rotor is balanced by placing it on pedestals instrumented with accelerators that detect forces generated by imbalance in the rotor. The electromagnetic field generated by the rotor during this process was simulated with Maxwell to ensure it did not interfere with the cables carrying the accelerometer signals.

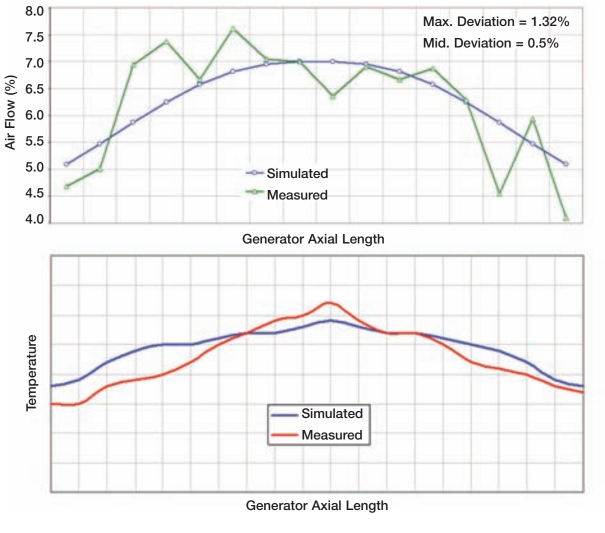
Fluid dynamics results show air flow variations over the length of the generator using three different cooling system options. The options involve modifying the geometry of the slot, windings and magnets.

Indar engineers simultaneously studied the generator's cooling system because of the interaction between electrical and thermal performance. The temperature of the magnet plays an important role in its ability to resist demagnetization, so improvements in cooling performance can increase the magnet's ability to handle a short circuit. Optimization of the cooling circuit helps to improve efficiency by reducing mechanical and cooling losses.

To optimize the cooling circuit, engineers used ANSYS FLUENT fluid dynamics software to perform a detailed study of fluid flow and heat transfer in and around the generator. Meshing was a challenge because of the difference in scale between the small 5 mm to 10 mm air gap between the rotor and stator, where accuracy was critical, and the large overall 1 meter length of the generator and cooling system. To minimize computational time, 3-D steady-state analysis was used during the majority of the design process, and the model size was reduced by using axial symmetry and periodic conditions. Fluid dynamics results included the local heat transfer coefficients, air flow velocity at every point in the machine circuit, pressure drop of the air circuit through the generator, generator temperature and thermal profile, and magnet working temperature. Engineers used these results as a guide in decreasing temperature hotspots by reducing variations in cooling over the length of the generator.

Using software from ANSYS helped Indar to easily explore multiple automated parametric design variations. The electromagnetic and fluid flow simulations provided far more diagnostic information than was available from physical testing. Simulation provides results for any output at any point in the computational domain, while physical testing provides results only at locations where it is practical to locate sensors. Engineers were able to iterate to a design that met all their specifications long before a prototype was built. Pervasive parameter management was performed quickly and easily by changing design parameters. These parameters were propagated throughout the entire design system, from CAD model through meshing and boundary conditions to generation of updated results.

The next step was building and testing a real-scale prototype to verify the simulation results and to ensure the generator's functionality and life expectancy. Two types of testing were performed at the test bench: generator full-load homologation testing to certify generator performance and durability testing to verify its reliability over time. The electrical and thermal measurements of the physical prototype matched up very well with the simulation results. For example, the maximum deviation from the voltage shape prediction to the measured values was 0.1 percent. The measured efficiency of the new generator was 97.86 percent, higher than the design target of 97.7 percent, and nearly exactly what was predicted by the simulation. The rating is one of the highest levels of efficiency for any permanent magnet generator on the market. Simulation made it possible to achieve this challenging performance goal in less than half the time that would have been required using conventional build-and-test methods. The simulation predictions correlated well with physical testing, providing confidence that Indar can use simulation to optimize its products to deliver high performance under the most demanding conditions.



The difference between the simulated and measured air flow rates across the length of the generator was a maximum of 1.32 percent. The maximum difference in calculated versus measured temperatures was only +/– 3 degrees C for the stator and +/– 3 degrees C for the rotor magnets. Software from ANSYS provided very good accuracy, which is essential for these applications and for Indar engineers to trust the new design variations.