Hydrogenerators Finite Element Modeling with Flux^{TM}

From conventional to renewable energy, from large-scale power plants to in-house systems, energy generation has to be efficient and sustainable to supply the grid and support the different needs. Whatever the source of energy is, the generators should convert motive power into as much electrical power as possible. From few kW to MW, Flux^{TM} can perform electromagnetic analysis that will enable to increasing generator performance. Hardly accessible equipment has to maintain their performance over the time. Therefore, extending their service life and averting any downtime that could affect production remains a necessity.

Flux™ can be used to build fault tolerant generators and latest generation of tidal equipment. Major faults in the machine such as abnormal connections in the windings (short-circuited or open turns, phase-to-ground, phase-to-phase faults) or rotor static and dynamic eccentricities, can be reproduced by simulation. The impact of the faults on the motor operation, as well as non-invasive fault detection methods can be evaluated for remote monitoring.

This article mainly focusses on the electrical engineering aspects of the design. Hydrogenerators parameters extraction and dynamical behavior prediction can be easily determined with a two-dimensional finite element modeling. Comparisons with experimental values have shown that a high accuracy can be achieved for classical or non-conventional tests, among them:

- No-load characteristic
- Synchronous inductance in the d- and q-axis
- Transient and sub-transient inductance in the d- and q-axis
- Field and damper winding inductances
- Standstill frequency response (SSFR)
- Form factors C_1, C_{ad} and C_{aq}
- THF factor
- Sudden short circuit analysis
- Force computation on the end winding
- Short circuit analysis
- Interaction of the alternator with its working environment (System simulation)
- Machine Design Exploration & Optimization
- A global Platform supporting Smart Grid Innovations

These tests can also be conducted with Flux on other types of rotating machines (turboalternators, induction motors, DC motors,…).

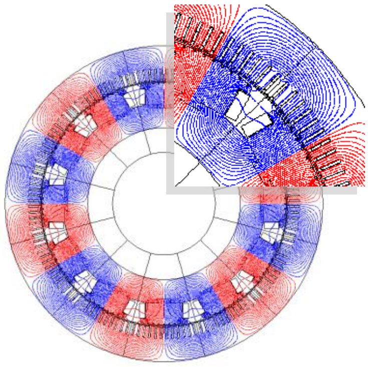
More information : Flux^{TM} software - www.altair.com/smartgrid

- We specially thank Daho Taghezout - Applied magnetics who helped writing this document. -

› Machine geometry and study domain

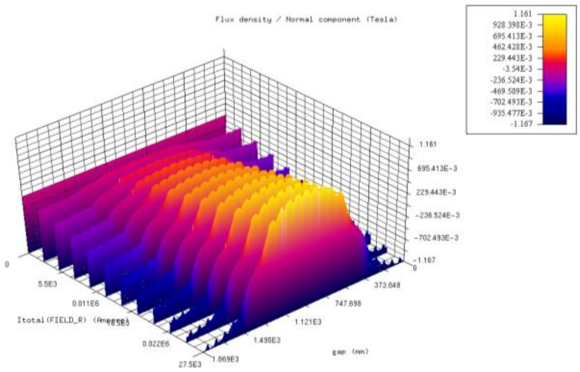
For hydrogenerators and other types of rotating machines exhibiting a periodic configuration, cyclic conditions are used in order to minimise the computation domain. For a full slot winding, one or two poles are usually modeled. With fractional slot windings, the minimum periodicity is required. By using Flux functionalities such as the coupling to electrical circuits it is easy to make static or dynamic tests on the generator. Moreover, Flux allows the computation of rotor torque, electric power, as well as iron and copper losses for steady-state and transient operation. As illustration of the software capabilities, the next sections will show some tests we have conducted on a full winding hydrogenerator.

› No-load test (U0-I0 characteristic)



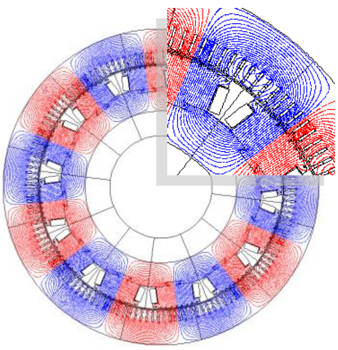
The figure above shows the Flux lines generated by the excitation winding on a hydrogenerator cross-section. By varying the excitation current from 0 to I_{f0}, we can draw the no-load U-I characteristic.

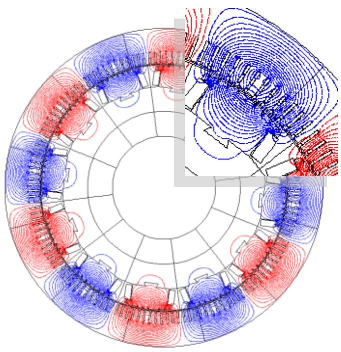
› Normal component of the airgap Flux density vs. field current at no-load



The normal component of the airgap Flux density can be displayed in a 3D curve (position on the x coordinate, Flux density on the y coordinate). In a non linear situation the Flux density varies proportionally to the field current.

› Synchronous inductance in the d- and q-axis (Ld, Lq)



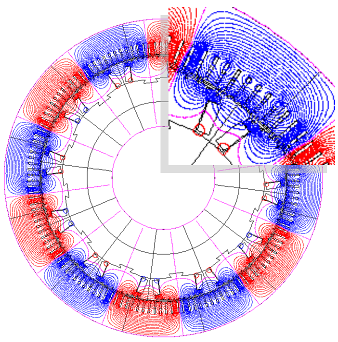


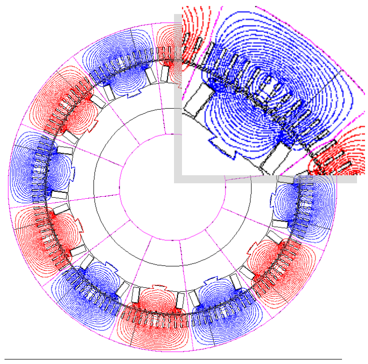
The synchronous inductance in the d- and q axis are determined through a magnetostatic resolution. The Flux software allows to freely move the rotor in any position during a magnetostatic analysis. Therefore, the pole axis is moved in order to be oriented in the phase A axis then 90 electrical degrees forward. Phase A is supplied with a current $\hat{I}$ and phase B and C with $-0.5\hat{I}$. The Flux coupled with phase A is equal to $L_d\ \hat{I}$ or $L_q\ \hat{I}$.

› Transient inductance in the d- and q-axis (Ld, Lq)

The transient inductance in the d- and q axis are determined with the help of a harmonic analysis. The damper short circuit ring is assumed to be open while the field circuit is short circuited. The information on the damper winding bars connection as well as the field winding connection are given through a coupling of the finite element domain to an electrical circuit.

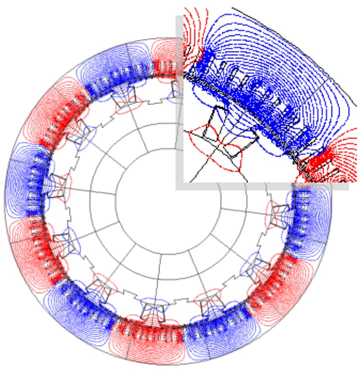
Phases A, B and C are supplied with a sinusoidal current shifted by 120°. The rotor axis is oriented along the phase A axis then 90 electrical degrees forward. The Flux coupled with phase A is $L'_d\hat{I}$, respectively $L'_q\ \hat{I}$.

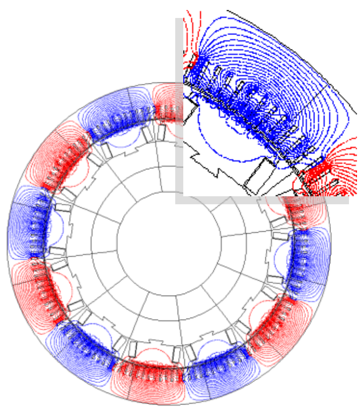




› Subtransient inductance in the d- and q-axis (Ld, Lq)

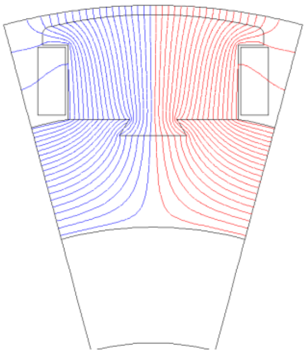
The subtransient inductances in the d- and q axis are determined with the help of a harmonic analysis. The damper and the field circuit are short circuited. Phases A, B and C are supplied with a sinusoidal currents shifted by 120°. The rotor axis is oriented along the phase A axis then 90 electrical degrees forward. The Flux coupled with phase A is $L''_d\hat{I}$, respectively $L''_q\ \hat{I}$.

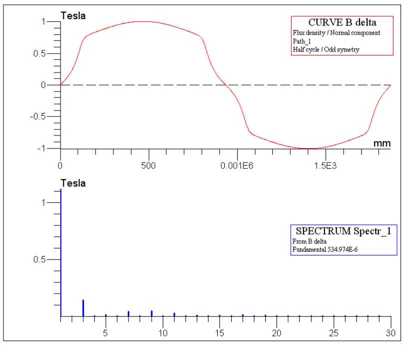




› C_1 form factor

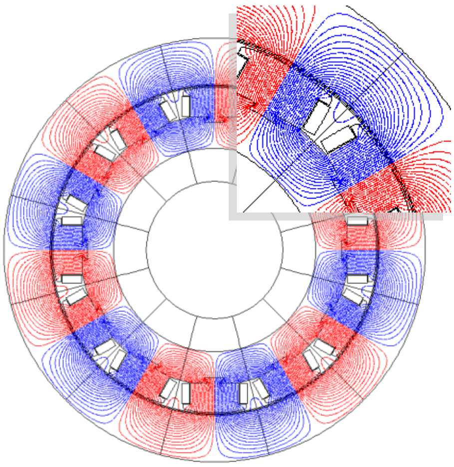
The C_1 factor is determined for one pole. The airgap width is equal to $\delta_0 k_c$, δ_0 being the minimum airgap and k_c the Carter factor. The iron is considered to be infinitely permeable. The stator bore is assumed to be a smooth surface. The field winding is supplied with a constant current. The normal Flux density in the airgap fundamental value and peak value yields the C_1 factor.

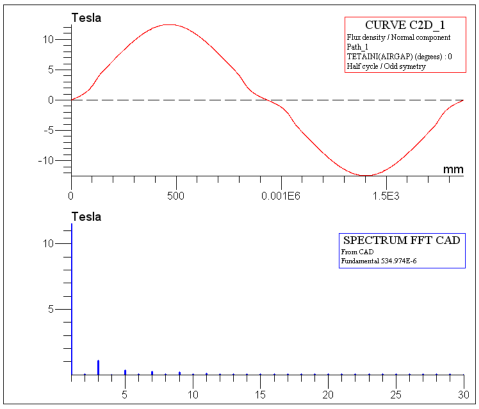




› C_{ad} form factor

The C_{ad} factor is determined for one pole. The airgap width is equal to $\delta_0 k_c$, δ_0 being the minimum airgap and k_c the Carter factor. The iron is considered to be infinitely permeable. The stator bore is assumed to be a smooth surface. The armature reaction is oriented along the d-axis. The normal Flux density in the airgap fundamental value and peak value yields the C_{ad} factor.

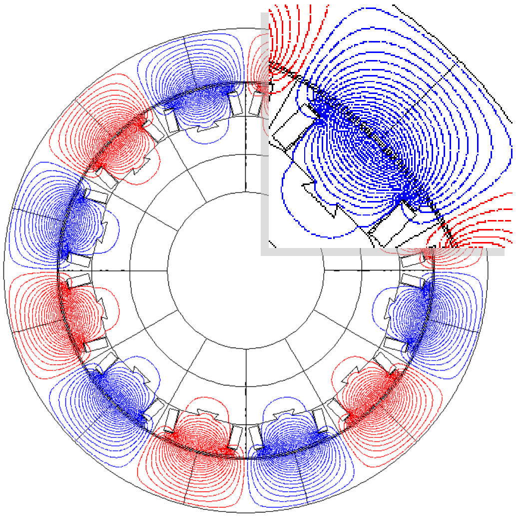


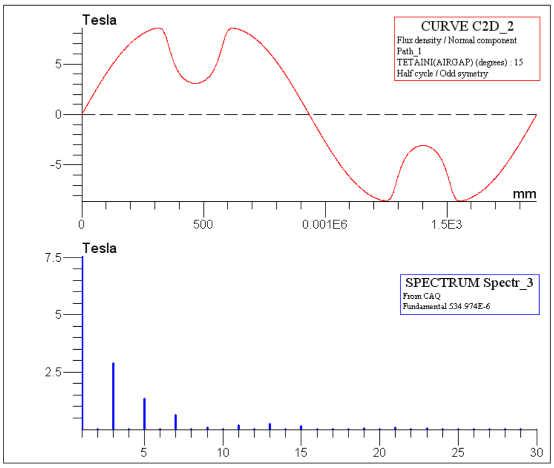


› C_{aq} form factor

The C_{ad} factor is determined for one pole. The airgap width is equal to $\delta_0 k_c$.

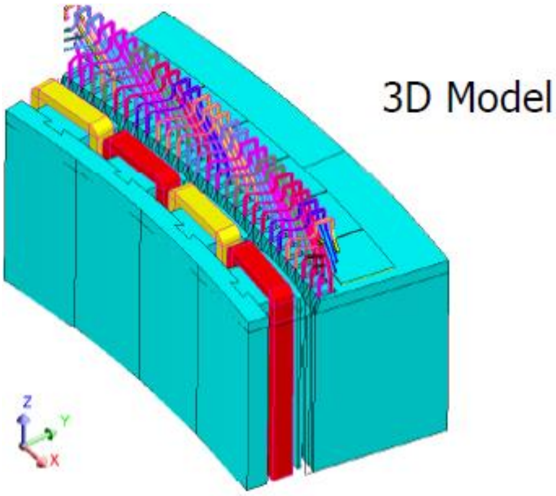
The iron is considered to be infinitely permeable. The stator bore is assumed to be a smooth surface. The armature reaction is oriented along the q-axis. The normal Flux density in the airgap fundamental value and peak value yields the C_{aq} factor.





› Force computation on the end winding

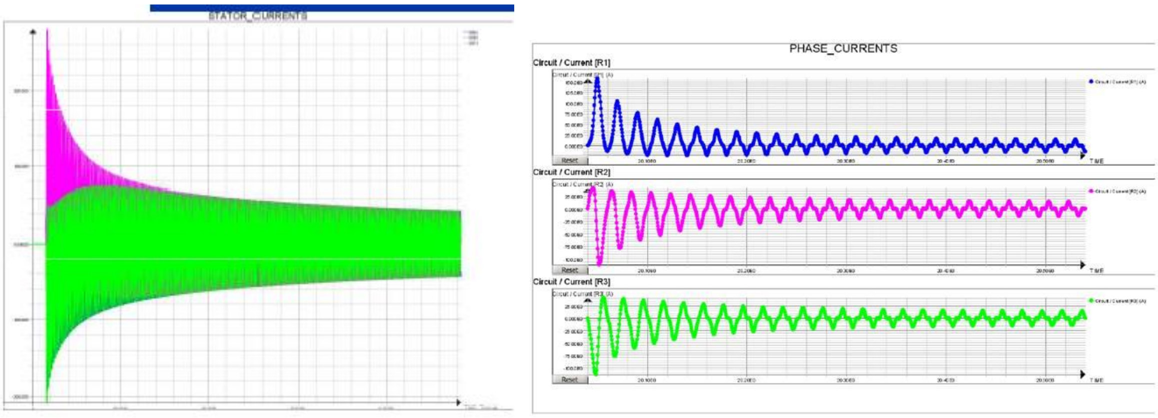
The aim of this study is to predict the Laplace forces, and to check the mechanical behavior and resistance in case of short circuits, including warming.



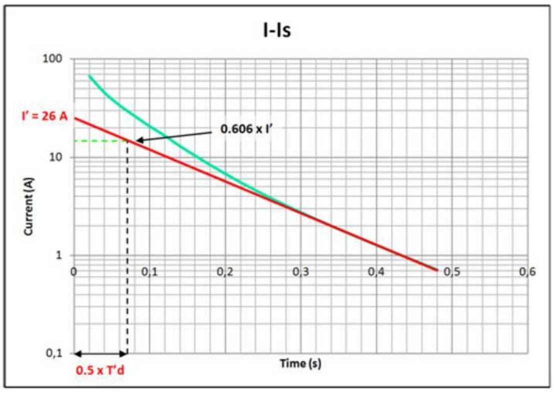
Non-meshed coils representation in Flux 3D offers interesting compromise between computation time and accuracy

› Short circuit analysis

Short circuit tests compute the transient currents in order to size the machine according to the mechanical torque ripples and forces resulting on the winding heads.

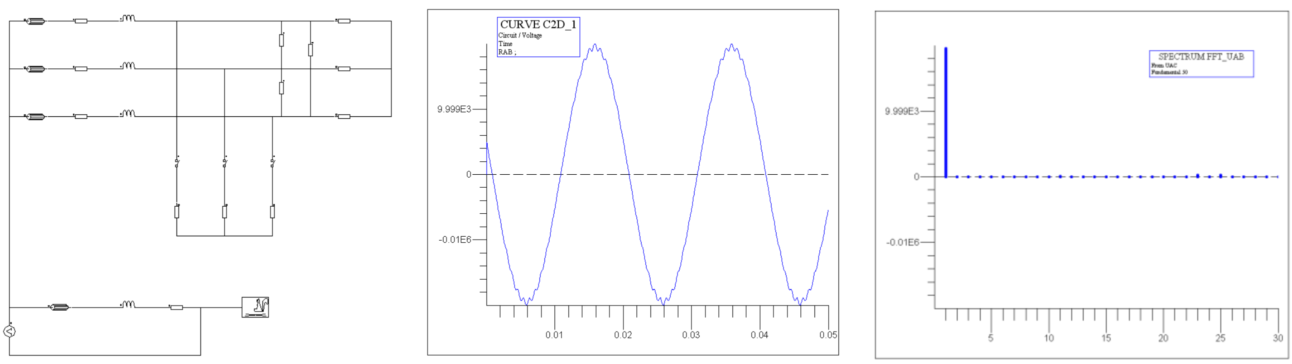


Current transient analysis in the coils coil with Flux 3D



Method for extracting data from short-circuit test

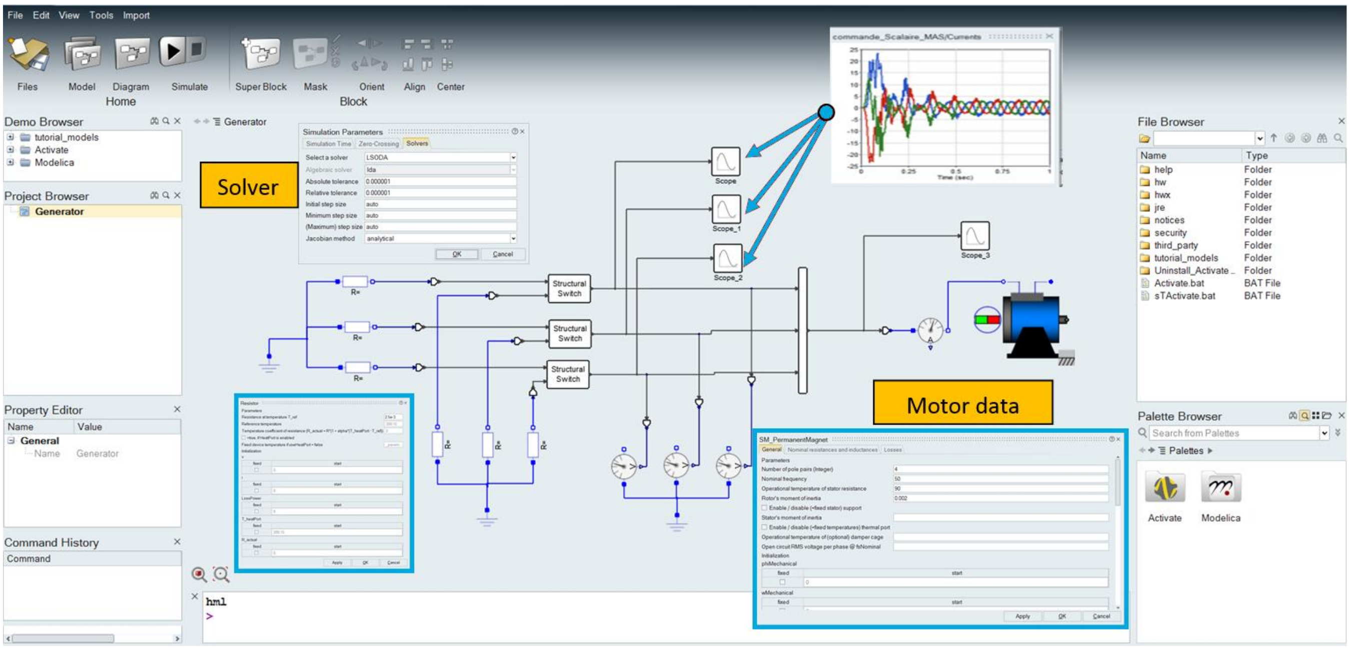
› THF form factor (influence of the damper winding currents on the THF factor)



The THF factor is determined in a transient analysis, with the rotor moving at constant velocity. The field winding is supplied with rated value and the damper winding is active. The oscillations on the stator terminals voltage are due to the damper currents variations as well as to the stator and rotor slots. The THF factor is computed from the no-load voltage harmonic components. The curves displayed above show the line to line no load voltage vs. time and its Fourier transformation.

› Interaction of the alternator with its working environment

By coupling the finite element software Flux to the system simulation software solidThinking Activate™, we can investigate the interaction of the alternator with its working environment using a complex non linear model and not a model based on the Park equations (figure below). It is thus possible to integrate transformers, transmission lines, turbine, regulation, machines in parallel,...

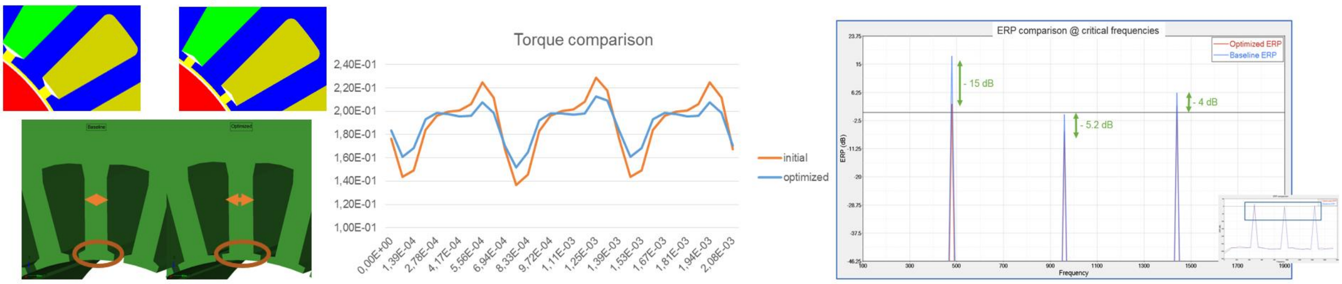


Sudden short-circuit investigation on a large hydrogenator

› Machine Design Exploration & Optimization

Design Exploration & Optimization are key factors in the improvement of any virtual prototyping process. Altair [HyperStudy®](#) multi-disciplinary design exploration & optimization tool helps engineers to efficiently come up with smart designs satisfying the specifications, and improve thus the engineering productivity. Using Design – Of-Experiments (DOE), metamodeling and optimization methods, HyperStudy® creates a set of smart designs, automatically evaluates these designs and collects data. Designers are then guided to understand data trends, perform trade-off studies and optimize design performance and reliability.

Coupled to Flux™, HyperStudy allows optimizing any device modelled in Flux, for instance to improve generator efficiency, reduce losses, minimize weight or improve reliability,... Moreover, the HyperStudy's seamless connection to HyperWorks enables to easily setup multi-physics optimization workflows involving different physical aspects (ex. mechanical and electromagnetic).



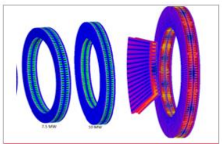
Machine multi-physics optimization example to decrease its noise while maintaining its performance
Coupling HyperStudy optimization with Flux electromagnetic tool and OptiStruct structural analysis

› A global Platform supporting Smart Grid Innovations

Altair has a wide variety of technology, multi-faceted experience and resources to help our customers build and maintain solutions that provide a competitive advantage in their particular areas of expertise.

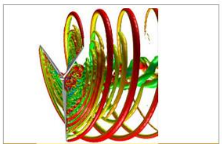
Three primary factors are at the core of Altair's impact on the Energy Industry:

- The rise of HPC and its near-universal availability, not just for large, established players, but also to small/medium-sized businesses
- The rapidly-shrinking development schedule and budget for everything from down-hole tools to carbon-fiber turbine blades
- The competitive advantages afforded by Computer-Aided Engineering (CAE) simulation and optimization



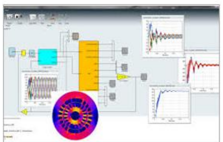
EM LF Flux

. Equipment efficiency . Equipment aging & anomalies prediction . Connected sensing & actuating functions



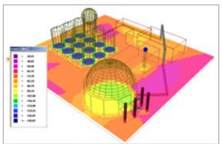
CFD AcuSolve

. Thermal radiation . Particle tracking . Turbulence



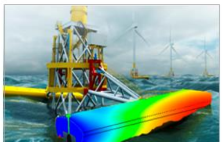
System Activate

. System-level simulations of power generation and storage . Performance characterization



EM HF FEKO

. Antenna, radar impingement . Wave propagation & network planning . EMC

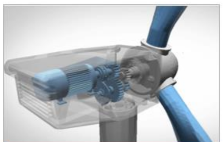


Structural OptiStruct

. Design Reliability and Robustness . Vibration analysis of primary structures . Safety validation

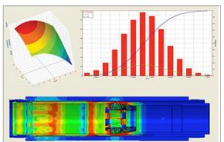
Hi.transient events RADIOSS

. Pipe rupture . Aircraft impact loads



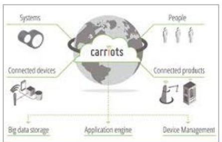
MotionSolve

. Power generation and lifecycle prediction



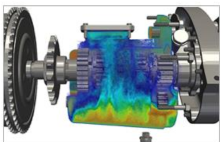
Optimization HyperStudy

. Design exploration . Multi-domain optimization, sensitivity and reliability analysis



IoT Carriot

. Big Data Analytics & Utilities . Remote monitoring . Digital Twin . HPC



& more

. Modelling tools . Complex geometries & motion flow . Risk reduction . Composite ...

More information: http://www.altairhyperworks.com/industry/Energy