Electric Drive Design
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EXECUTIVE SUMMARY

Electric drives are found in all areas of transportation and industrial automation and cover power ranges from fractional to thousands of horsepower and beyond. Design of components of electric drives systems or the even more challenging task of designing sub-systems or systems belonging to the electric drive applications area is of great interest to many electrical engineers. The main reason for this interest is the current trend for electromechanical energy converters to replace traditional hydraulic systems and, more generally, mechanical systems. This trend will continue and even accelerate due to significant benefits of weight and cost reduction, increased reliability of electrical systems, and convenient control and automation via electric and electronic means.

Fig 1. Electric drives applications
The trend to utilize more electric drives significantly impacts the requirements users have for simulation tools.

- component, sub-system and system-level simulation are all desirable since this global approach allows both concentration on component performance but also makes possible the end-to-end simulation of the final product;
- the physical nature of the application may require the consideration of thermal and/or stress consequences of electromagnetic fields;
- integration in the simulation environment of productivity features such as parametrics sweeps, optimization, statistical analysis and distributed solving (on computer network) provides additional benefits to users.

The needed attention to detail requires accurate design and simulation of many components along the energy flow channel. Logical consequences of this requirement are both the need of the component-level simulation tool to communicate with the system-level simulation tool and the consideration of thermal and stress consequences of electromagnetic fields at the component level.

Ansoft provides a unique set of integrated tools that makes the global design and simulation of sophisticated electric drive systems and components inherently thorough, accurate and intuitive for engineers.

*Fig. 2 Typical electric drive system configuration*
Maxwell® is software for the simulation and analysis of high-performance electromagnetic and electromechanical components. The software allows users to study static, frequency-domain, and time-varying electromagnetic fields in complex structures.

Simplorer® is multi-domain, system simulation software for the design of high-performance electromechanical systems. The software includes a wide range of modeling techniques and statistical analysis capability, adheres to IEEE modeling standards, and allows engineers to study design performance of electrical, mechatronic, power-electronic, and electromechanical systems.

ePhysics™ provides the ability to perform thermal and stress analysis and couple the results to Maxwell to determine electrical, power dissipation and mechanical integrity constraints.

The ability to import high-fidelity component models from Maxwell into Simplorer ensures accuracy at the system-level simulation. Additionally, the automatic data link between Maxwell and ePhysics enables for the simulation of thermal and stress effects of the components.
In many situations, particularly for medium voltage and high short-circuit current applications, major manufacturers of vacuum-operating switching devices (Siemens, ABB, etc.) use contacts with specially shaped contact geometries to achieve superior performance required by the application. Thus, over 100,000 switching cycles can be achieved while being able to ensure reliable large short-circuit current (tens of kA) interruptions of over 100 times during the lifetime of the vacuum interrupter. Both radial and axial magnetic field topologies are used in such high-performance vacuum interrupters (Fig. 4).

This superior performance was in part due to FEM simulation of different contact geometries using particular distribution of conductive and magnetic material properties. As a result, a favorable distribution and dynamics of the electric arc between contacts can be studied and optimized. In a radial magnetic field contact topology, an azimuthal electromagnetic force acting on the vacuum arc forces the arc to move over the surface of the contact at a high speed of around 100 m/s, with favorable effects on the aging of the surfaces and capable of improving the reliable current interrupting ability.

Axial magnetic fields (two- or four-pole axial magnetic field in the contact gap) configurations can be explored with available FEM simulation tools capable of predicting the distribution of current and magnetic field at arbitrary locations inside the device and the phase shift between currents and corresponding magnetic fields with important consequences on the dynamic of the electric arc.

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**Fig. 4. Vacuum interrupters and respective contact sub-assemblies**

**Fig. 5. Geometry and current distribution of a high-performance electric contact used in a vacuum interrupter operating at medium voltage**
Similar concerns regarding reliable switching and capability to interrupt high short-circuit currents face designers of low-voltage switching devices. For this area of switching applications, the configuration of the device (circuit breaker) is very different. Here, too, the concern is to use various techniques, many times a combination of techniques aimed in essence at extracting as much energy as possible from the burning electric arc.

The model in Fig. 6 exhibits an arc divider/extinguisher chamber as well as an integrated coil, both with different, distinct roles in the process of reliably interrupting the current (normal current or short-circuit current). For such devices, the distribution of magnetic field and conduction current is important. Fig. 7 shows examples of post-processing in such an application: Current density and magnetic field magnitudes are presented as well as a parametric study of the force calculation acting on the electric arc (simulated as a cylindrical, conducting plasma channel).

![Fig. 6 Model of circuit breaker courtesy of ABB Schweiz AG](image1)

![Fig. 7a. Current density distribution and magnetic field distributions](image2)

![Fig. 7b Lorentz force distribution on the arc and force vs. position, parametric study](image3)
In Fig. 7b, the plot represents the variation of the force acting on the electric arc plasma as the respective electric arc is “attracted” inside the ferromagnetic walls of the extinguisher. The parametric study was performed by using Maxwell’s distributed processing capability by solving different variations on parallel computers.

However, in this application of equal interest are the thermal and stress consequences of electromagnetic fields. Indeed, for both normal operation regime and fault (short-circuit) regime, the thermal and stress behavior of the device is of intense interest for designers. To extend the simulation capability into the investigation of the thermal and stress consequences of the currents flowing in the device, Maxwell is coupled with ePhysics. The nature of the coupling is dynamic in the sense that once the communication channel has been established between the two desktops, needed data flows automatically and allows the adaptive meshing technology to be used in both. For this reason, since the meshes in the two-coupled model may be different, an adequate mapping is used and applicable for the power loss density as well as for the force distribution, respectively, depending on the application.

The coupling between the Maxwell and ePhysics desktops is much more general than the situation presented in Fig. 8 and covers all types of electromagnetic solutions from static ones to transient ones. Also note that the dynamic datalink technology used for the coupling allows parameter mapping between coupled designs such that the full automatic nature of the coupling can be used even in complex parametric sweeps.

Using the technology sketched above, Figs. 8a and 8b present the temperature distribution and deformation respectively of the parts of interest.

**Fig. 8a Temperature distribution, thermal steady-state simulation**

**Fig. 8b. Thermal deformation of the current path, deformation is amplified for visualization using a convenient scale**
Inductors are used in many electric drives applications. Inductors may be used as part of filters to provide current smoothing effects or di/dt limitations as needed by the application. Their design involves an electromagnetic analysis phase, but thermal and/or stress effects also may be investigated. Shunts, used mainly for DC current measurements, are modeled in a similar way. Typical examples of inductor geometries are presented in Fig. 9.

![Different inductor geometries](image1.png)

**Fig. 9 Different inductor geometries; left: quarter model, right: high current, full model**

Inductor modeling (as the modeling of many other electromagnetic devices) is possible from a dual perspective: a component analysis using a field solution (Maxwell with or without coupling with ePhysics) but also from the perspective of exporting the electromagnetic essence of the device as an equivalent circuit with field effects. Thus, using the ECE feature available in Maxwell, inductance and resistance of components can be exported in a convenient format for sub-system/system-level analysis in Simplorer. Fig. 10 shows how such equivalent models with field effect can be exported from Maxwell for use in a sub-system or system-level simulation together with other components.

![Equivalent circuit export panel](image2.png)

**Fig. 10 Equivalent circuit export panel (Maxwell -> Simplorer)**
Using the Maxwell-to-ePhysics datalink, the power-loss density distribution is mapped from the eddy-current solution to the thermal transient model. The respective temperature distributions at user-selected times are then used to obtain a sequence of static stress solutions using the respective ePhysics stress solver. The results of this chained example are shown in Fig. 11.

Note that in the above example, each of the steady/static solvers is using its own adaptive meshing solution (as set by the user) while the thermal transient simulation is performed with fixed mesh (final mesh in the eddy-current solution) and its own adaptive time-stepping algorithm.

In many drives applications (particularly in large power), the role of the power transformer can be very complex. Let us consider the sophisticated medium-voltage Harmony drive from Siemens AG, Fig. 12.

To achieve the needed medium voltage, the above solution uses a power transformer with many (9 – 18) phase shifted secondary windings and a series connection of power cells to reach the input/output power quality parameters and the desired level of voltage to be applied to the motor. There is no additional reactance between transformer and cell, so the commutating inductance of the diode bridge is entirely due to the leakage inductance of the transformer. This creates an interesting design problem, as the transformer losses are greatly affected by the harmonic content of the secondary windings.

For the electromagnetic design of the transformer, Maxwell is used to produce a very large inductance matrix. In an 18 secondary winding transformer, there are at least 37 coils, giving a matrix with 666 coupling factors. This very large equivalent circuit (the inductance matrix) is then exported to Simplorer for further analysis of the system. Other transient simulations are performed in Maxwell using the harmonic spectrum predicted from the Simplorer simulation (see paragraph D for more info).

The thermal simulation of such large units (1,100 KVA in this case) is also a challenge. Fig. 13 shows a typical situation with forced air cooling used.
Thus, the thermal modeling of this application makes use of sophisticated forced convection boundary conditions in ePhysics that are based on customer-supplied measurements of air velocities in all convection channels in the model. Examples of measured temperatures and the respective match with simulation results are presented in Fig. 14.

<table>
<thead>
<tr>
<th>Temp Rise</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>67</td>
<td>76.1</td>
<td>72.3</td>
</tr>
<tr>
<td>Simulated</td>
<td>70.6</td>
<td>80.5</td>
<td>70.7</td>
</tr>
</tbody>
</table>

A good match was also reported for the primary and secondary winding steady-state temperature simulation with forced/natural convection and radiation boundary conditions (as applicable, depending on location).

Medium-voltage transformers pose other design challenges as well. For example, the model shown in Fig. 15 is analyzed from an electrostatic field simulation perspective.
For this application, the requirement of simulating with high accuracy the maximum level of electric field in critical areas leads to the need to model real curvatures in the respective regions and perform adequate meshing such that the magnitude of the electric fields in the respective regions is adequately and realistically simulated. Using specific geometry modeling and applying mesh operations in Maxwell, the subsequent model that uses also automatic adaptive meshing is capable of rendering the high electric field magnitudes in the targeted regions (Fig. 16).

Bus-bar systems are used in most high-power electric drives applications. For such applications, the bus bars are capable of carrying typically hundreds to thousands of amps, sometimes even more. Fig. 17 presents an extreme application with a system of bus bars and cables capable of carrying over 100,000 A (RMS).

Fig. 15 Example of bushing application for medium/high-voltage transformer

Fig. 16 Shows main area of interest and electric field solution superimposed on local mesh (detail)

Fig. 17. 150,000 Amps (peak) system used in steel smelting plant
For such very large industrial size applications, many aspects are of interest, from the level of fields in the neighboring regions, adjacent biological aspects, shielding and thermal and stress simulation of such large shield systems and of the bus-bar system itself. However, for most drives, the usual type of bus bar used to transfer the power is contained inside a cabinet, such as shown in Fig. 18.

Fig. 18 Medium voltage electric drive cabinet (from Siemens AG) Bus-bar capacity: 2,000 A

For this bus-bar application, the requirement is two-fold: of interest are the R, L and C of the different sections of the bus bar (to be used in a system-level simulation together with other components of interest) and the thermal and thermal stress simulation as well.

Fig. 19 Geometry of two components of the bus-bar system

The equivalent circuit parameters are extracted using Q3D Extractor®. For the thermal and stress simulation, we use Maxwell and ePhysics. Fig. 20 presents the result of the simulation, temperature distribution and the corresponding thermal stress under rated current flow conditions.

Fig. 20 Temperature distributions (above) and scaled deformation (below)
PCBs containing components, ICs, power electronics devices, IGBTs, FETs and SCRs, are eligible mainly for thermal (steady-state or transient) simulations. In most cases, a stand-alone ePhysics simulation is used for these specific applications, but, of course, the combination with Maxwell also is useable in the same applications.

As an example, let us consider Fig. 21, which presents a Maxwell (eddy current) design coupled with ePhysics thermal steady state. The respective simulation concentrates on the weak point of the design, the hot spot in the connecting wire, which gets to dangerous levels of temperature.

![Fig. 21 IGBT model, geometry (left) hot wire temperature (right)](image)

For the thermal analysis of PCBs in most cases, unneeded detail (from a thermal perspective) is not included in the models. PCBs with many layers of copper and FR4 are modeled, for example, as thermally anisotropic structures. ePhysics has the capability to use anisotropy settings for the material properties in both thermal and stress solver modules. There are situations, however, where the geometry complexity is manageable, and the problem can be solved using its full complexity. Such is the case of the model shown in Fig. 22, exhibiting a PCB with a few layers of copper traces and ICs.

![Fig. 22 Power amplifier circuits on a PCB](image)

Stress modeling also proves necessary in some PCB applications, such as is the case presented below, where a “bed of pins” model simulation is shown. The model uses an anisotropic setting for the material property of the multi-layer PCB and over 200 applied points of pressure. A study of placement of the anchor points is then performed such that deformation of the PCB is kept within specified limits.

![Fig. 23 Deformation distribution simulation results example (plot of displacement magnitude)](image)
Electric machines are usually difficult to simulate. There is the question of the modeling approach to use; an analytical approach (less accurate in general but very fast) vs. a finite element approach. Both methods are possible in the Maxwell desktop, which integrates analytical modeling (with RMxprt™) and accurate 2D/3D FEM analysis using field solvers. The advantage of using the Maxwell desktop is that different levels of abstraction (and accuracy) are possible for the simulation while making the data transfer between the available tools quite easy, as shown in Fig. 24.

RMxprt provides an efficient way of creating the challenging geometries (2D and 3D) and material properties setup for models exported to Maxwell. RMxprt also exports equivalent circuit models that are used in Simplorer. There is a very similar data flow between Maxwell 2D and 3D (geometry and material properties), allowing efficient data transfer for increased productivity in simulation at the desired level. Maxwell includes many additional features for electric machine simulation:

- 3D nonlinear anisotropy modeling
- Lamination models
- Core loss modeling available in transient simulations
- Dynamic demagnetization computation
- Non-Cartesian coordinate systems
- Integrated schematic capability for electric circuits coupled with the windings of the machine
- Distributed processing for large parametric simulations
- Equivalent circuits exported to Simplorer

Thus, the range of electric machine applications possible to simulate using Maxwell is very large. A few of the available examples are presented below. In Fig. 25, the plot on the right-hand side of the picture shows the benefit of using the multiple processor option for solving a large stepper motor model. The timesavings with this option become even more significant when deep saturation effects need to be investigated.
The brush-type DC motor model presented in Fig. 26 makes use of commutating elements embedded in the library of elements available for use in transient applications. The simulation uses the capability of making the contact resistance at the interface between brush and commutator bar a function of position, such that the respective effect is considered automatically during the simulation. Mechanical elements connected to the moving part, such as load force/torque, inertia, and damping, can be specified during set-up.

Some of the results of the simulation are shown in Fig. 26. Note that a whole range of results are available for post-processing, some of which are calculated automatically (winding current, flux linkage, back EMF, torque, core loss, etc.); others can be specified as additional quantities to be calculated by the field calculator.

For electric machines, the thermal and mechanical stress consequences are two other distinct areas that can now be investigated using the available couplings between Maxwell and ePhysics. The following example is the result of cooperation with Siemens AG (Large Drives, Nuremberg, Germany) who provided the model, material properties and thermal test measurement data for comparisons.

The synchronous, permanent magnet electric motor analyzed from a thermal performance perspective has a max of 600 KW output and is used in a completely new gearless drive system for future high-speed trains. The configuration in which the thermal performance is analyzed is presented in Figs. 27 and 28.
Fig. 27. PM motor in a direct drive configuration

Fig. 28 PM motor configuration details
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![Fig.29 Symmetry model used in the thermal modeling of the PM motor](image)

Other modeling features used in the thermal simulation were the anisotropic distribution of thermal conductivity of the laminations for the rotor and stator, two power levels and two inlet cooling fluid temperatures taken into account, convective and radiation boundary conditions used for external surfaces, and temperature-dependent cooling fluid properties.

Simulation of the above-described device, performed in ePhysics, showed a good match with experimental data for all regions of the motor. As an example, Fig. 30 presents temperature distribution in the rotor and permanent magnets, useful information due to the possible impact on the performance of the motor.

![Fig. 30 Temperature distribution in permanent magnets](image)

The match of permanent magnets temperature distribution at three locations (the two ends and middle) was within 5% of the respective measured values. The same good agreement was reported for the windings and stator locations, showing a clear anisotropic behavior of the motor mainly due to the gradual heating of the cooling fluid mixture (50%-50% water and ethylene glycol).

In some PM electric motors (such as in embedded PM rotor configurations) operating at high speeds, analyzing the stress and deformation due to a combination of electromagnetic and centrifugal body forces distributions is critical in the design process. Indeed, due to the embedded PM topology used for the rotor in this application, for these motors, the thickness of the bridge must be thick enough to withstand the stress due to the combined forces and yet adequate also from an electromagnetic perspective to allow easy saturation of the material. These two possibly conflicting requirements must be balanced in such a way that both constraints are satisfied. In Fig. 31, the stress and deformation distribution for such a rotor operating at 10,000 rpm is shown.
ePhysics also can be used to determine the stress distribution for a given placement of the heavy components inside the drive cabinet. Fig. 32 presents an example of such an application that provides the displacement distribution of the frame only when moved by an overhead crane in the assembly plant.
The usage of system-level simulation for electric drives simulation cannot be overestimated. The current level of complexity in this area combined with the increasing need for accuracy in the simulation makes the availability of system components with field effect more than a trendy technology; it clearly defines a viable market. Thus, the combination of Maxwell and Simplorer, which allows the creation and use of equivalent components with field effect, becomes a very useful tool in the hands of the system design engineer. Adding the possibility of using the dynamic coupling between Maxwell and Simplorer allows users to get a full picture of the multi-dimensionality of the coupling between the two desktops.

For drives applications, it becomes increasingly important to model in an efficient but also accurate way the complexity of many applications in this area. The equivalent models of transformers, inductors, bus-bar systems and motors—to mention just a few, all available from the Maxwell desktop—provide the convenience, ease of use and needed accuracy of the system-level analysis of electric drives. The following paragraphs provide a few examples along the above lines.

The example presented below shows the usefulness of having a field solver and a system-level simulator working together to simulate the over-voltages occurring in a low-voltage drive for a PWM driven AC motor. The model chosen for the electric cable is a low loss model, which does not take into account the distributed (transversal) conductance of the cable. It does take into account the distributed self and mutual inductance capacitance of the cable. Resistance may also be included in the equivalent model. Using a number of such “cells,” a model with distributed parameters is included in Simplorer as shown in Fig. 33 (only 5 “cells” shown) in such a way that the actual length of the cable is reflected in the model. The motor model used in this application corresponds to a 10 HP, 460 V induction motor.

The combined effects of the PWM of the applied voltage, the distributed nature of the cable model, which exhibits a certain characteristic impedance and the impedance mismatch with the induction motor model, are the reason for the over-voltage predicted by the Simplorer simulation. (Fig. 34)

![Fig. 33 Example of a building block in the Simplorer application for the study of the consequences of the reflected waves](image-url)

![Fig. 34 Motor terminal voltage plot](image-url)
The impact of the power transformer (the component-level model of the unit was presented earlier in the C. Electric Drives Components Design chapter of this paper) on the drive assembly is very important to simulate before the prototype is built due to possible consequences. One of the advantages of the Harmony drive is the quality of power input and output with very low distortions. The transformer windings are usually extended delta configurations, with different numbers of turns in the interior and exterior of the delta to achieve the necessary phase shift.

For the electromagnetic design of the transformer, Maxwell is used to produce a very large inductance matrix. In an 18 secondary winding transformer, there are at least 37 coils, giving a matrix with 666 coupling factors. Fig. 35 shows a small part of the large inductance matrix calculated by Maxwell and exported into Simplorer to be used in the system-level model of the variable frequency drive.

The voltage amplitude and phase shifts must be closely controlled to achieve best-input harmonic results. The task here is to obtain a transformer that has suitable properties to function properly in this application and not incur excessive losses. The overall drive model is presented in Figs. 36 and 37 and contains the transformer equivalent circuit (inductance matrix) models of the IGBTs and the control logic.

Fig. 35 Inductance matrix (self and mutual inductances) of the power transformer

Fig. 36 System-level model of the drive, sub-sheet containing power transformer and rectifying bridge

Fig. 37 System-level model of the drive, sub-sheet containing switching devices and switching PWM complex logic
Using the system-level model in Simplorer, a thorough analysis of the drive is performed. Thus, the impact of the transformer design on the quality of the power is assessed. The match with measured data is excellent. Fig. 38 shows the cell input currents as an example. The same good match is observed for the output quantities, which confirm the very small distorting harmonic contents.

![Fig. 38 Side by side measured and simulated input cell currents](image1)

![Fig. 39 Output voltages and currents plot](image2)
BENEFITS OF THE INTEGRATED APPROACH = VIRTUAL LAB ENVIRONMENT

Ansoft tools are integrated to provide the accuracy and ease of use engineers involved in the analysis and design of electromagnetic components and systems require. Particularly for electric drives applications, the integrated approach and access to functional datalinks between desktops provide a comprehensive simulation environment. Realistic, virtual tests can be performed and complex analysis undertaken to obtain data to validate design choices and scenarios. The functionality provided by the seamless integration of Maxwell, RMxprt, Simplorer and ePhysics provides multi-domain solving capability that is ideal for electric drives applications.

One of the “signature” characteristics of the integrated approach solution is the dynamic datalink technology used for communication between Ansoft modules. Thus, once a link between any two or more desktops has been specified, the data will flow through the user-specified channels without any other intervention needed from the user. Let us look at a typical scenario involving, for example, Maxwell and Simplorer, with Simplorer using an inductance matrix from Maxwell in a system design model. In this case, once the link between the two designs in the respective desktops has been designated, Maxwell design parameters are visible in the Simplorer environment and can be used automatically in optimization tasks of the whole system. Thus, when a new variation solution from Maxwell is needed in Simplorer due to a parameter value change (for example, a different relative orientation between magnetically coupled coils), the new Maxwell solution process is automatically initiated via the data link; once it becomes available, the new information can be used in the system-level design tool. Maxwell can be “driven,” in this example from Simplorer, by a user who may not have previously worked with Maxwell. Thus, simply the knowledge about where an applicable Maxwell design resides is sufficient to create the datalink and use it to extract and use necessary information in the respective desktop environment.

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ABOUT THE COMPANIES

ABOUT ANSOFT

Ansoft is a leading developer of high-performance electronic design automation (EDA) software. Engineers use Ansoft software to design state-of-the-art electronic products, such as cellular phones, Internet-access devices, broadband networking components and systems, integrated circuits (ICs), printed circuit boards (PCBs), automotive electronic systems and power electronics. Ansoft markets its products worldwide through its own direct sales force and has comprehensive customer-support and training offices throughout North America, Asia and Europe. For more information, please visit www.ansoft.com.

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Siemens, headquartered in Berlin and Munich, is one of the world’s largest electrical engineering and electronics companies. Siemens provides innovative technologies and comprehensive know-how to benefit customers in 190 countries. Founded more than 150 years ago, the company is active in the areas of Information and Communications, Automation and Control, Power, Transportation, Medical, and Lighting.

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