Equivalent-Circuit Extraction for System-Level Modeling of Three-Phase Synchronous Machines

The equivalent-circuit extraction (ECE) method automatically generates an efficient system-level model from a magnetic finite element method (FEM) model of a radial-flux three-phase synchronous machine. FEM allows detailed analysis and optimization of the nonlinear time-dependent electromagnetic characteristics of synchronous machines. The ECE method allows the characterization of the nonlinear magnetic characteristics of the machine into a circuit and system simulator, thus permitting optimization of the complete drive system.

Products Used
ANSYS® Maxwell®, ANSYS Simplorer®, ANSYS Optimetrics™, Distributed Solve option (DSO)

Keywords
Synchronous machine, finite element method (FEM), distributed analysis, system simulation, drive system simulation, real-time simulation

System-Level Modeling of Synchronous Machines

State-of-the art design of electric machines typically employs finite element methods to optimize parameters such as torque, efficiency and induced voltage. Using FEM tools such as ANSYS Maxwell, a designer can perform design variations of geometry, material properties, electrical supply characteristics and mechanical loading to optimize magnetic design.

However, an optimized electric drivetrain must consider the interaction of the machine with electrical and mechanical components of the complete system, as well as the effects of controller behavior. To this end, magnetic design of the machine must be validated and optimized in the context of the drive system, including:

- Battery or DC-link capacitor
- Power electronics
- Control software
- Mechanical drive components

ANSYS Simplorer provides a platform for complete drivetrain simulation. To incorporate transient machine dynamics in the system model, you need a circuit-level representation of the machine. Direct transient cosimulation with the magnetic FEM design allows for a high-fidelity simulation incorporating all transient effects. However, simulation time for this cosimulation can be prohibitive for dynamic simulations involving controls and mechanics in the range of many seconds. Such simulations may need several days to run on today's hardware.

The equivalent circuit extraction procedure generates a system-level model of a three-phase synchronous machine based on the results of a magnetic FEM analysis — yet it allows simulation times several orders of magnitude faster than for cosimulation. The method captures the main nonlinear magnetic effects of saturation and slot effects. The resulting model is defined by a set of nonlinear differential equations that describe the relationship between phase currents of the machine and magnetic flux. Typical analyses possible with this model are:

- Harmonic analysis of voltage/current, torque
- Control system dynamics
- Short-circuit protection

The model is suitable for use in implicit differential-algebraic equation (DAE) solvers, such as ANSYS Simplorer, as well as for explicit solver approaches for real-time hardware-in-the-loop simulators.

ECE Parameter Extraction Technique

The ECE technique has been implemented for a three-phase electrical machine represented as a transient model in Maxwell 2-D. The technique is applicable for all three-phase machines in which induced eddy currents play a subordinate role in the flux linkage. The method can be applied to both permanent-magnet machines (BLDC, ASSM, etc.) as well as wound-rotor synchronous machines. An extension of the method to handle six-phase machines and/or 3-D models is feasible. The characterization procedure is shown in Figure 1.

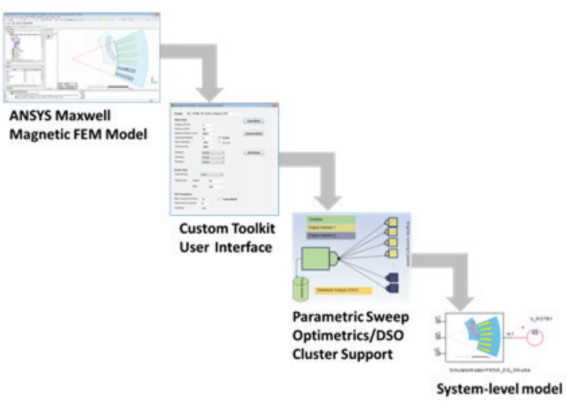

Figure 1. Automated ECE procedure

The input data for the characterization is a three-phase transient Maxwell 2-D model. The Maxwell model must contain at least three winding definitions (for a PM machine) and at least four winding definitions for a wound rotor (including exciter winding). Existing rotational symmetry can be taken into account. Using a customized toolkit user interface, the user simply inputs basic machine topology (number of poles, number of slots, maximum current, etc.), as shown in Figure 2.

Once the machine parameters have been entered and validated, pressing the generate-model button starts the automatic characterization of the machine. A parametric sweep-varying input current and rotor position is performed, and the resulting magnetic flux for each variation is determined. Using the ANSYS Distributed Solve option (DSO) technology, the parametric sweep can be distributed across multiple machines in a network cluster. The result of the parametric sweep is a lookup table of magnetic flux as a function of stator current, field current (for a wound-rotor machine) and rotor position. This table information can be read by a custom machine model written in C and compiled as a dynamic linked library (*.dll) for the Simplorer system simulator.

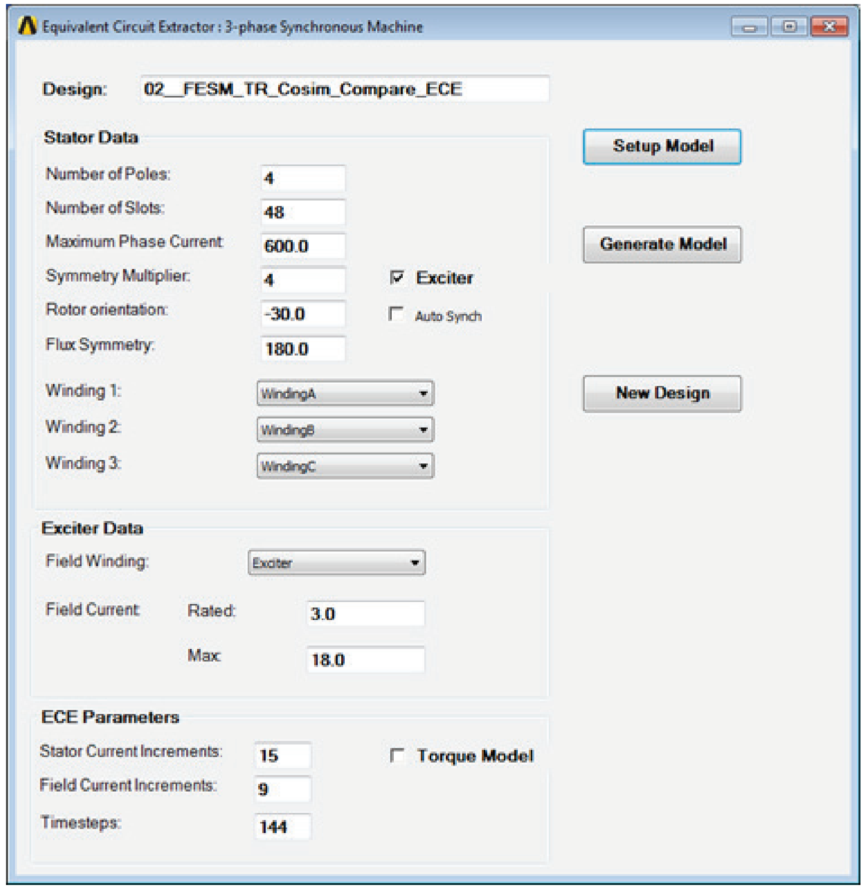

Figure 2. Toolkit user interface for ECE

Extension to Real-Time Simulation

Validation of real-time control software requires simulation models capable of running in real time. So-called hardware-in-the-loop simulators represent the physical plant incorporating difference equations solved explicitly using very small sample times (< 100 ns) to ensure numerical stability. The numerical methods used for this ECE model can be readily adapted into synthesizable VHDL code for use in HiL simulators. This extension can be performed for a customer-specific configuration in collaboration with ANSYS consulting services.

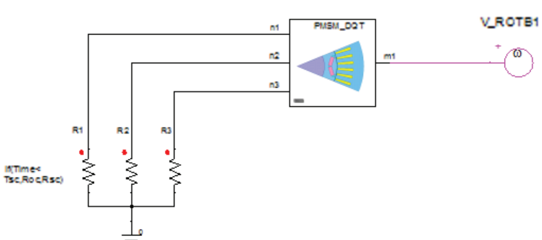

Figure 3. Simplorer test circuit: constant mechanical speed of 5,000 rpm, resistive load on stator windings switched from 1,000 Ω to 0.1 Ω at t = 5 ms

Simplorer System Model Example

A simple test circuit (Figure 3) was developed to validate the ECE model and to compare results and simulation time with FEM cosimulation. For the validation, a 50 kW three-phase interior permanent-magnet machine based on an early Toyota Prius design was used. The machine is operated at constant mechanical speed of 5,000 rpm. At t = 5 ms, the terminal resistance is reduced from 1,000 Ω to 0.1 Ω, representing the transition from no-load to short-circuit operation.

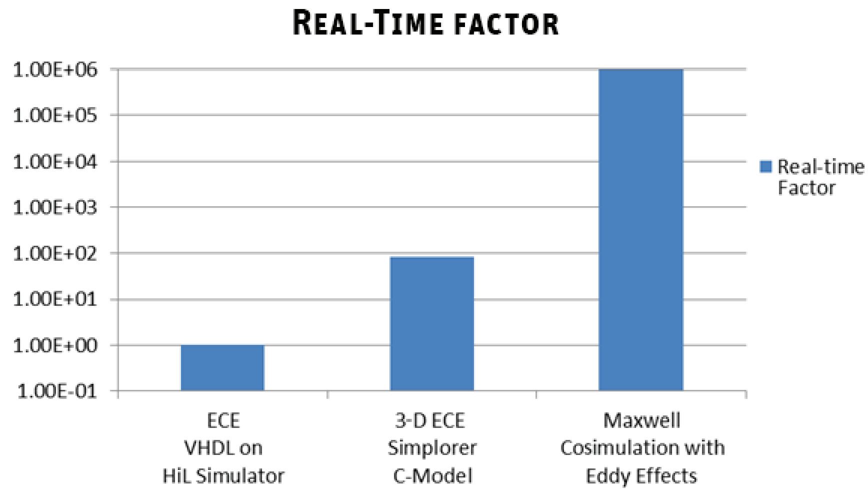

Figure 4. Real-time factor (ratio of simulation time to real-time) for various ECE and cosimulation models

In Figures 5 through 8, a comparison between the full transient FEM model with the characterized ECE model is made. Note that the results are very similar. The difference between the two curves is due to the contribution of eddy current effects to transient behavior. The primary effects of magnetic saturation and slot effects (cogging) are accurately represented by the ECE model. The ECE solution runs at a factor of 1e4 times faster than the full cosimulation model, thus allowing for efficient system optimization with minimal error.

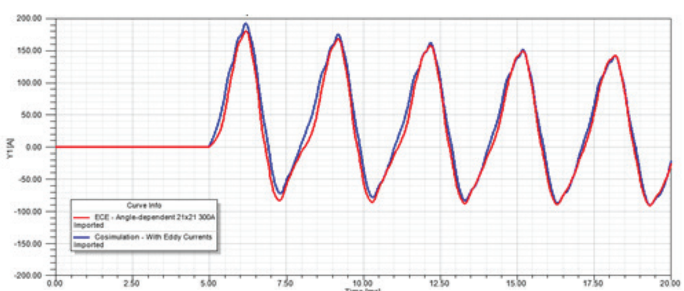

Figure 5. Torque produced by Maxwell FEA motor model

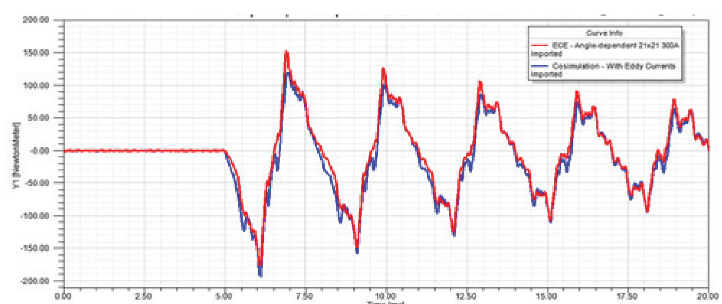

Figure 6. Comparison of short-circuit air-gap torque: ECE vs. transient FEM cosimulation

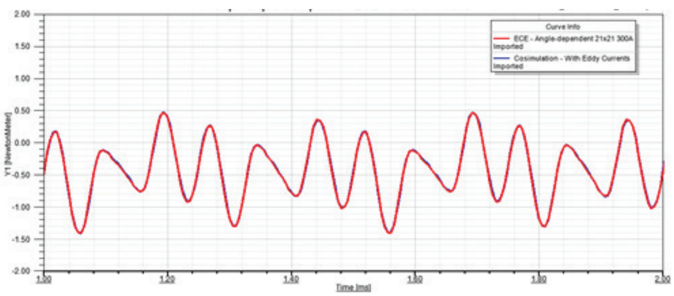

Figure 7. Comparison of cogging torque at no-load: ECE vs. transient FEM cosimulation

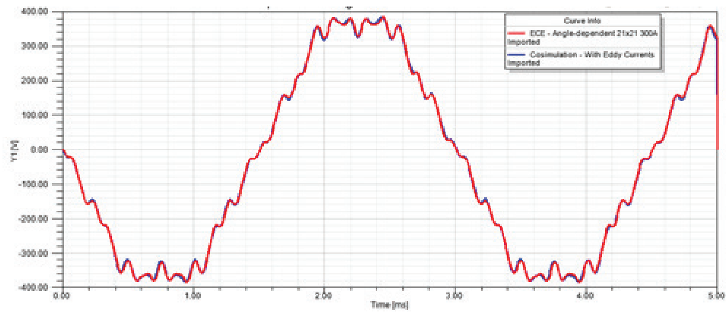

Figure 8. Comparison of back-emf at no-load: ECE vs. transient FEM cosimulation

Summary

ANSYS software solutions address multiple engineering domains that are inherent within today's modern motor and drive systems. The ability to integrate nonlinear electromagnetic motor models to circuit and system simulation enables engineers to consider the total design at different levels of abstraction without trying to integrate incompatible design software.

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