APPLICATION BRIEF

Ansys Maxwell Automation and Customization

The prediction of efficiency maps in the traction motor design stage is a crucial development for the optimal operation of hybrid electric vehicles (HEV/EVs). The motor designer must ensure that the motor produces optimal efficiency in the speed range and road-load profiles during drive cycles.

Reduction of permanent magnet (PM) materials in electric machines is of interest to many machine manufacturers and designers, as the cost of rare-earth materials is not stable. The impact of changing a machine design parameter, such as the shape of the magnets, may have consequences, including efficiency reduction and effects on torque quality.

This application brief depicts an efficiency map computation and compares it with measurements for a permanent magnet synchronous machine, including the complete torque-speed operating region. The validated simulation model led to an investigation of reducing the permanent magnet size, which enabled reducing the magnet size by 20%. The impact of this on efficiency and machine performance was quantified, and design changes were simulated that maintained the desired efficiency over the operating range.

To achieve the goals set earlier, Ansys developed tools to automate the design process of an electric machine. A set of user-defined solutions were scripted using Python and completely integrated into Ansys® Maxwell® desktop (Figure 1). This facilitates further complex post-processing analyses. The following properties are in the developed UDO scripts:

- Generalized.
- Automated.
- Accurate.
- Efficient.
- Ease of use.
- Extendable.

The electric machine design toolkit consists of advanced solutions for the following:

- Efficiency map computation.
- Efficiency map displayer.
- Torque speed curve computation.

Calculating torque-speed curves and efficiency maps is very challenging in finite element analysis (FEA). The toolkit not only runs the simulation, but it also (and most importantly) finds the optimal operation points.

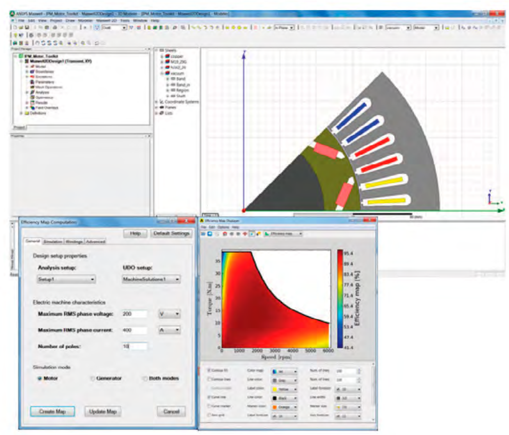


Figure 1. Electric machine design toolkit to compute complex design performances.

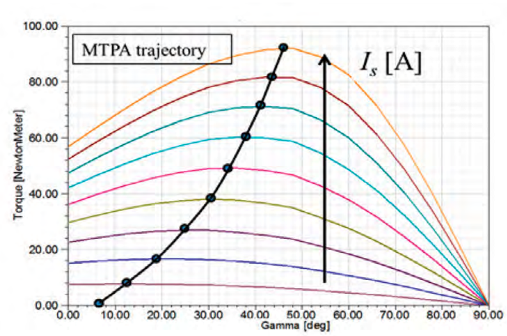


Figure 2. Concept of MTPA illustrated in torque vs. current angle and magnitude.

/ Efficiency Map – Method of Computation

The maximum torque per ampere unit (MTPA) control strategy (Figure 2) is employed to compute the efficiency maps as:

- At a given operating condition, the trajectory of the current is crucial for optimal efficiency operation of PM machines.
- By varying the input voltage, there can be an infinite number of I_d and I_q combinations that can produce the required torque at a given speed.

MTPA strategy is applied. The scheme results in minimizing the stator current and, thus, maximizing the efficiency below base speed, assuming that the winding loss is dominant.

In flux-weakening regions, output power is maximized, and apparent power is minimized to improve power factor.

The MTPA control algorithm finds the optimal current angle that gives the minimum current at a given torque. An evolutionary algorithm based on nondominated sorting genetic algorithm (NSGA-II) with (Pareto) dominate solution and combined with spline interpolation technique is used for the optimization.

In this study, the MTPA control strategy is implemented in the experimental and simulation work to obtain efficiency maps for interior PM machines. The simulation is conducted with a time-domain 2D FEA model. The machine is assumed to be current controlled, and, thus, sinusoidal currents are used in the FEA simulations. The method of computation of the efficiency map consists of the following steps:

1. Simulate a parametric sweep of transient simulations for different current magnitudes and angles, γ, at a constant speed to obtain a family of voltage and torque curves that are tabulated and used in spline interpolation.
2. Apply the MTPA algorithm using multi-objective optimization to calculate the operation points (I_d and I_q) for the torque-speed range in motoring, generating or both modes. An evolutionary computation, NSGA-II with (Pareto) dominate solution, is used.
3. Run the final simulations using the calculated operation points found with the MTPA. These operation points are simulated at the whole torque-speed range to compute the core loss and eddy-current magnet loss at different supply frequencies.
4. Compute the efficiency from the output power and total losses that include winding loss, core loss, eddy-current loss in the magnets and mechanical loss.

The method offers the following advantages:

1. Requires only voltage and current limits as inputs and automatically applies the MTPA algorithm and computes the optimal control angle at the whole torque-speed range accordingly.
2. Requires running only a parametric sweep of the current and current angle at a single speed. The torque is assumed to be independent of the speed in current-fed machines. The voltage is assumed to satisfy constant volts per hertz relation. These are considered to be valid assumptions in synchronous machines in which the losses, including core loss and eddy-current loss, have minimal influence on the torque and back emf production.

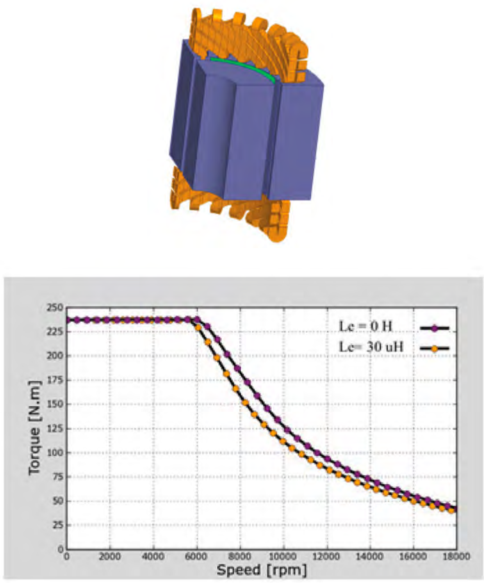


Figure 3. End-winding inductance calculation.

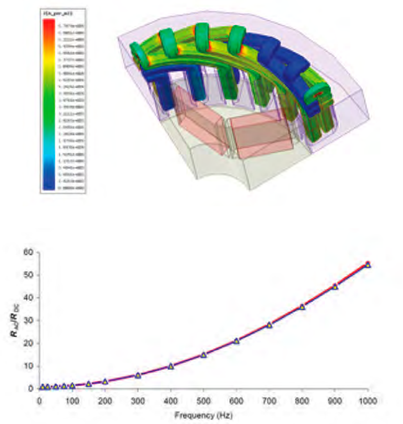


Figure 4. AC resistance of stator windings calculation.

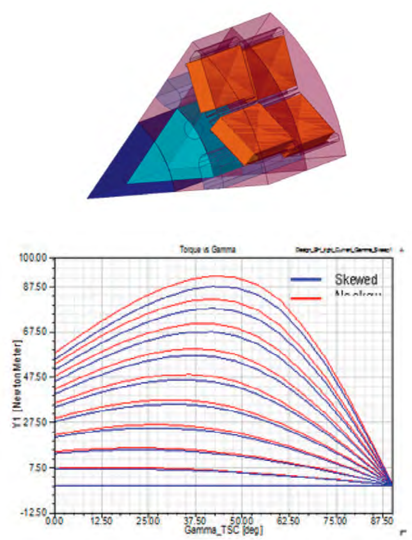


Figure 5. Skewing effect on torque profile.

3. Integrates various vital effects, such as skewing, DC/AC winding resistance at rated temperature, end-turn winding inductance, frequency-dependent core loss coefficients and mechanical loss.

The computational method implemented into the toolkit considers, in the same time, dynamic effects of end-winding (Figure 3) manifested in the torque-speed profile, AC winding resistance (Figure 4), temperature dependency, core-loss and skewing effect on back emf and torque characteristics (Figure 5).

Figure 6 shows few quantitative results based on the applied efficiency map computation method. Thus, various machine characteristics are computed as torque-speed, current-speed and power-speed.

In a similar manner, other important characteristics are obtained, as illustrated in Figure 7.

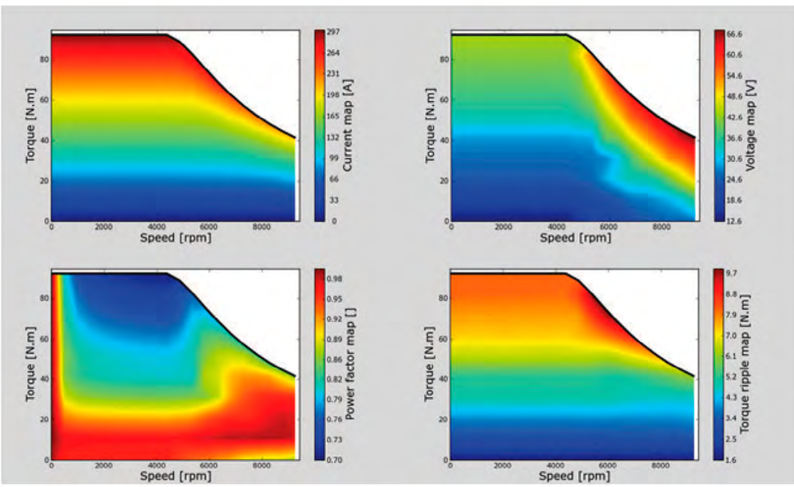
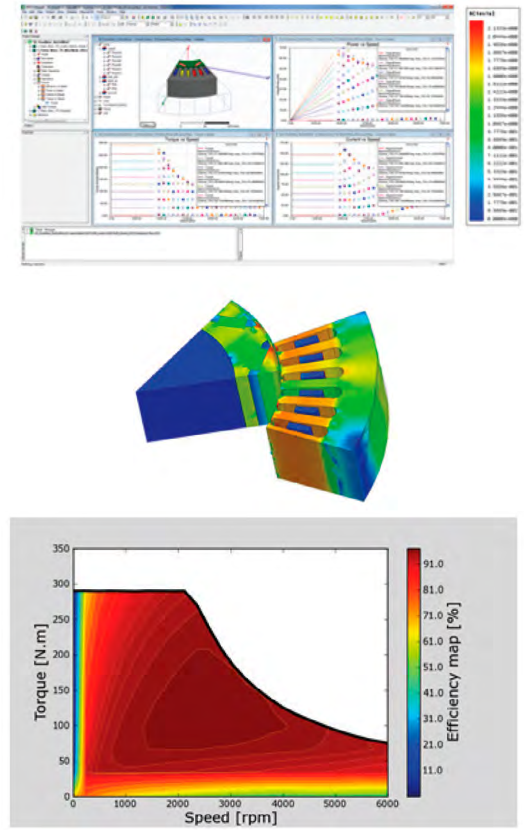


Figure 6. Efficiency map representation: (top) various speed profile characteristics; (middle) magnetic flux density distribution; (bottom) efficiency map.



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