Leveraging Automation to Generate Efficiency Maps for Electrical Machines in ANSYS Maxwell

This paper describes efficiency maps generated automatically in ANSYS® Maxwell® for predicting a motor's performance under a broad range of operating scenarios.

Simulating electric machine designs saves time, reduces the number of hardware prototypes and enables innovation. ANSYS Maxwell allows engineers to create and test a wide range of digital prototypes of electric machines, and iterate to achieve optimal designs. Template-based design capabilities allow engineers to automatically generate virtual prototypes by specifying appropriate values for typical machine parameters such as the number of phases and poles, slots, materials, motor diameter, coil pitch etc. So, even when CAD files are not available, engineers can turn to these templates to automatically generate machine designs of their choice. Maxwell offers insight into how machine designs can be improved and optimized by analyzing their electromagnetic performance and thermal behavior, limiting their noise vibration effects and understanding their interaction with relevant power electronic devices. Using ANSYS Maxwell for designing and simulating machines dramatically reduces the number of hardware prototypes, saves costs, boosts reliability and shortens the time to market.

Design considerations for motors must include a wide range of operating conditions involving speed, torque, current, power, etc. For instance, a modern electric vehicle's drive motor is expected to offer instant high torque for acceleration and high power at high speeds for cruising, enabling high efficiency operation of the vehicle. Such functional requirements can pose stiff challenges to engineers who create, control and optimize motor designs so that they perform reliably in a variety of operating conditions. The problem is, an optimal design for a low-speed, high-torque condition may not be suitable for the converse operating requirement of high speed and low torque. For a given speed and torque, engineers also need to determine the best way to operate a machine while also limiting its power consumption. Solutions to these problems can be found through accurate simulations in ANSYS Maxwell. You can design a motor that meets specific operating conditions without losing sight of its expected performance across multiple other operating scenarios as well. ANSYS Maxwell can help mitigate these design challenges through its automated efficiency maps, which empower engineers to design, test, evaluate and optimize a motor's behavior over wide-ranging operating scenarios.

Efficiency Maps

An efficiency map is a graphical representation of a motor's performance over its entire operating range. Typically, it is depicted as a contour map. The X-axis represents the rotational speed of the machine. The rotational speed is input data for the simulations/experiments. The Y-axis represents the torque of the machine, which evaluates the rotational force delivered by the motor. It is an unknown quantity, and its values are found through simulation. Finally, the plotted quantity is primarily the efficiency of the motor: the ratio of the power delivered by the motor (output) to the power delivered to the motor (input power).

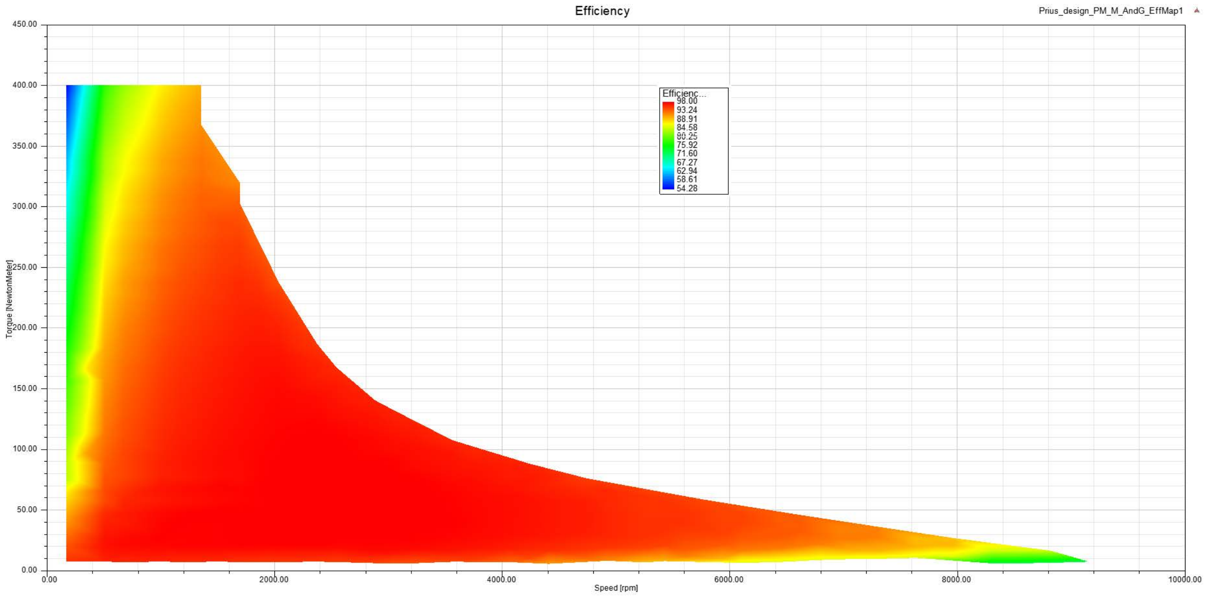


Figure 1. Efficiency map

Efficiency maps help engineers understand how to operate the motor at maximum possible efficiency. In addition to efficiency, engineers can plot other useful quantities like current, voltage, loss, inductance etc.

Efficiency maps are obtained through many discrete simulations. Each point on the efficiency map is the result of running an optimization over several valid operating conditions of the motor. That being said, how do we virtually determine all the valid points that build the efficiency map? We need to solve a large parametric sweep that comprises all viable and practical operating conditions of the machine.

To find the best way to operate a motor at a given speed and torque among all possible candidate scenarios, we have to determine and understand all the scenarios through simulations. The number of scenarios could range anywhere between 200 to 2,000 or more. To understand each scenario, a transient FEA simulation must be performed, which can be costly and time-consuming for such a large number of runs. Fortunately, ANSYS Maxwell offers the powerful, built-in Design of Experiments (DoE) capability to simplify this large problem and considerably reduce the design space. DoE limits the number of candidates that need to be considered. Instead of solving all possible cases through a parametric table with combinations of all input data, DoE enables engineers to build the parametric table and generate data required by a response surface technique. Everything is generated in an automated fashion in ANSYS Maxwell. Once the efficiency maps are produced, engineers get a good understanding of the machine's behavior across a broad range of practical scenarios. The next section describes the automated process.

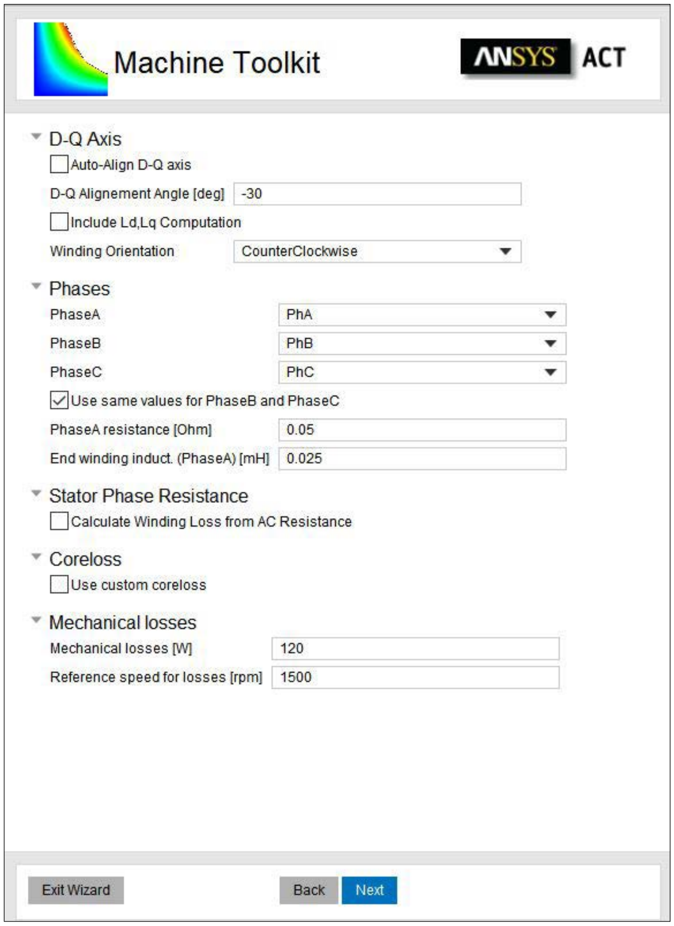
Automation of Efficiency Maps Creation

In ANSYS Maxwell, efficiency maps are automatically generated as follows.

Step 1: Input machine parameters

The machine parameter inputs for calculating the efficiency maps consist of the following:

- A ready-to-solve 2D or 3D model of a motor suitable for a transient analysis.
- Machine characteristics that are described by the number of poles, the excitation type, amplitudes etc.
- Upper values of operating conditions such as maximum rotational speed and maximum current voltage, as well as the level of intervals between values (more intervals will lead to more accurate representation).
- Desired optimization method (MTPA — Maximum Torque Per Ampere or Torque Loss Minimization).



☐ Auto-Align D-Q axis
D-Q Alignement Angle [deg] -30
☐ Include Ld,Lq Computation
Winding Orientation CounterClockwise
PhaseA PhA
PhaseB PhB
PhaseC PhC
☑ Use same values for PhaseB and PhaseC
PhaseA resistance [Ohm] 0.05
End winding induct. (PhaseA) [mH] 0.025
☐ Calculate Winding Loss from AC Resistance
☐ Use custom coreloss
Mechanical losses [W] 120
Reference speed for losses [rpm] 1500

Figure 2. Machine Toolkit

Step 2: Build and solve all possible candidates

From the inputs (the number of intervals and maximum values of operating conditions), a parametric table is built. Each row of a parametric table represents an acceptable operating point. After the simulation of all the candidates, the torque and efficiency are evaluated.

The size of the parametric table depends upon the type of electric machine and the desired level of accuracy. For example, a permanent magnet machine can be characterized with a table of a few hundred rows, whereas induction machines may require several hundred rows or more.

To accurately evaluate each row, a time domain analysis is performed. Solving the parametric table through domain decomposition or distributed solve (i.e., using multiple instances of the solver on separate cores) significantly reduces the simulation time by speeding up the entire solution process. Depending upon the total wall clock solve time, it's possible to calculate multiple efficiency maps in a single day — all needed to run an optimization.

Let's look at a few cases to measure the actual simulation time.

Case #1: Internal Permanent Magnet (IPM) Machine Solved in 2D

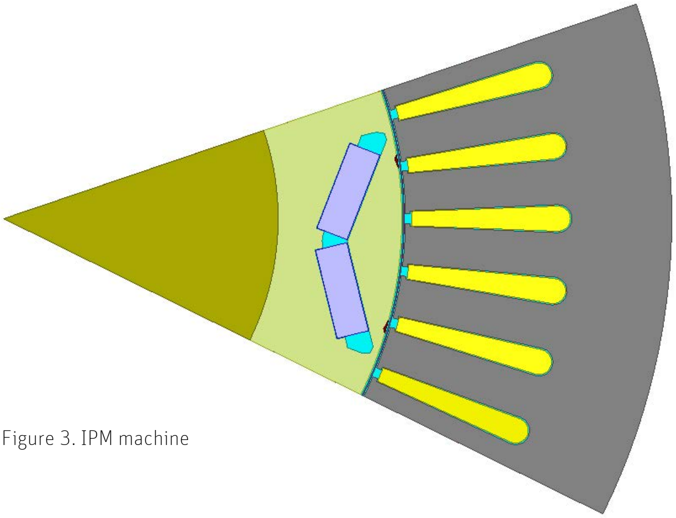


Figure 3. IPM machine

To obtain the efficiency map, about 250 simulations were performed in ANSYS Maxwell. As this machine topology is a synchronous motor, only two periods are necessary in a time domain simulation to generate the solution. Below is the time required to solve the parametric table.

Number of Cores	Solve time	Speed Up
1	2h 19min	
10	17min	8.1 times faster

Using just 10 cores, four different efficiency maps in an hour can be achieved.

Case #2: Induction Machine Solved in 2D

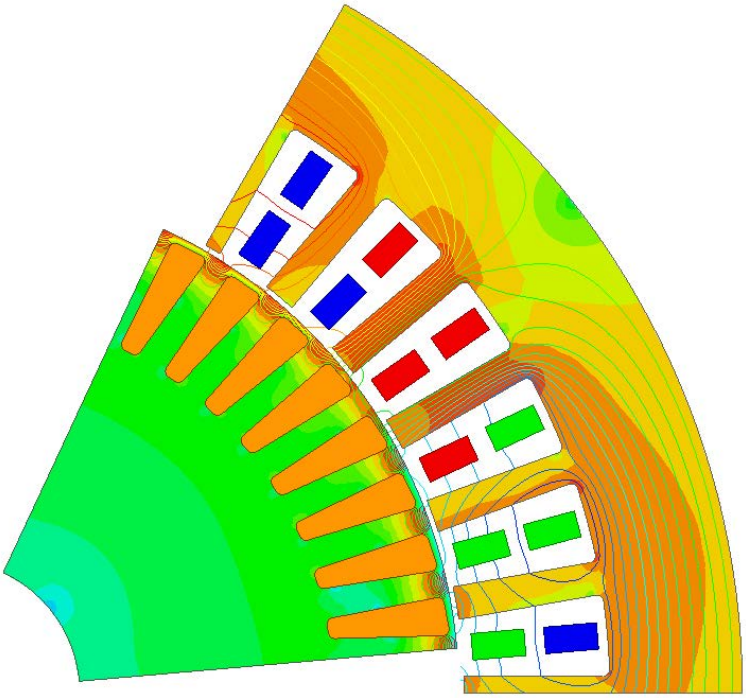


Figure 4. Induction machine

We solved an induction machine with extreme accuracy. The input parameters include number of current values, the number of slip values and the number of speeds. At the end, the size of the parametric table is 2,250. Because of the particular electromagnetic behavior of an induction machine, each simulation can be fairly long, because reaching a steady state can take anywhere from a few electric periods to 25+ electric periods.

Number of Cores	Solve time	Speed Up
1	~32 days	
10	3days 20h	8.4
120	11h 55min	65

Having deliberately chosen to solve the induction machine for extreme accuracy, it was imperative to use multiple cores to accelerate the simulation and compute the efficiency.

Case #3: Permanent Magnet Machine in 3D

Finally, in some cases, 3D simulation is necessary. Here we have an IPM with a stack of skewed magnets for which 2D simulations are not accurate enough. We also wish to capture the end inductance effects.

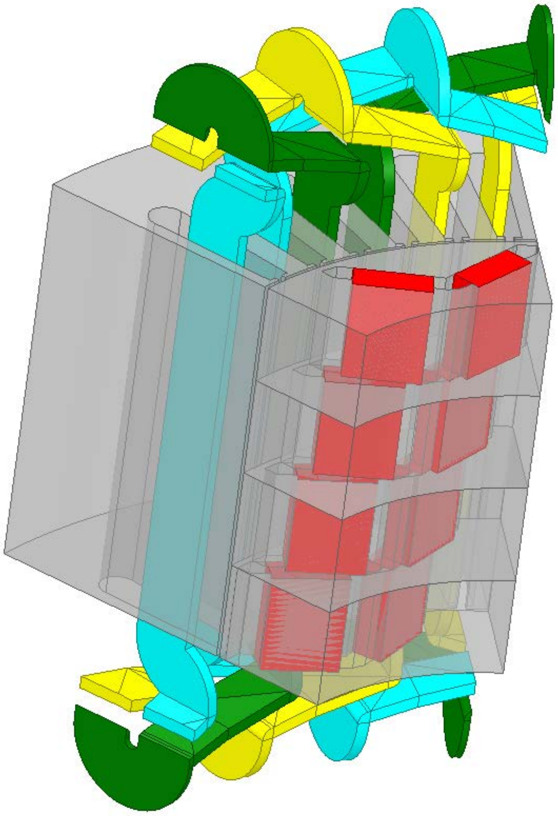


Figure 5. 3D Model of a PM motor

Number of Cores	Solve time	Speed Up
10	3days 22h	
120	10h 51min	8.7

Using 120 cores, it is possible to get a full 3D efficiency map in half a day.

Step 3: Extract results from candidates

Once the parametric table is solved, you can automatically extract all quantities that are necessary to identify the best candidates:

- Average torque
- Current/voltage values
- Core loss and solid loss over last period
- Inductance (Ld, Lq values)

Only these quantities are necessary to start the optimization if needed again. Therefore, the field quantities or solutions do not need to be saved.

Step 4: Find optimum operating conditions

Based on user input, the optimization process obtains the best candidates for all the operating conditions of the machine. It starts with filtering: some solutions are above the prescribed max current/ max voltage. Then, a reduced order model of the motor design is created based on the inputs for a 3D response surface. The response surface is built upon the output. Finally, the DoE analysis runs using the response surface to obtain the optimal operating points.

Step 5: Output efficiency maps and other maps

Post-processing and visualization offered by graphical representations in ANSYS Maxwell are important. For instance, the contour plots are populated automatically based on the optimization outcomes, and a series of efficiency maps is created.

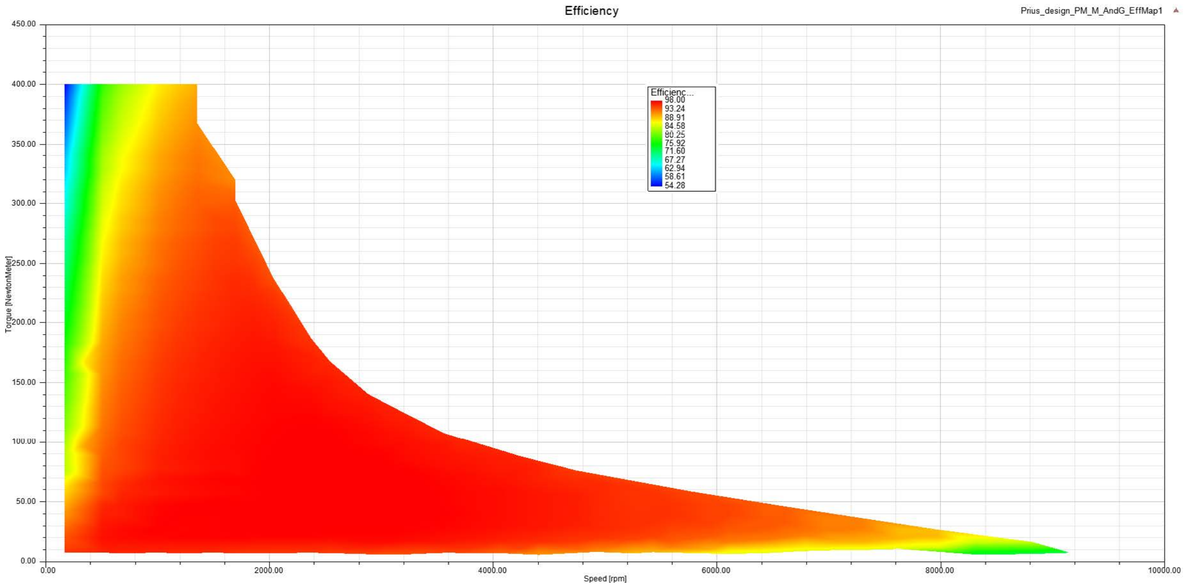


Figure 6. Efficiency map

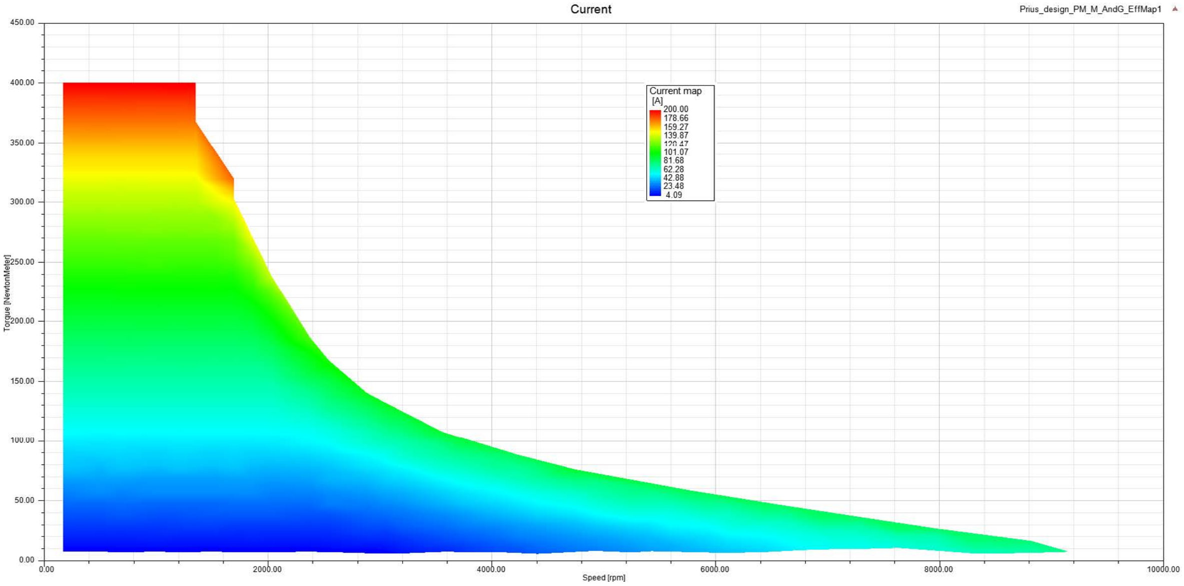


Figure 7. Current map

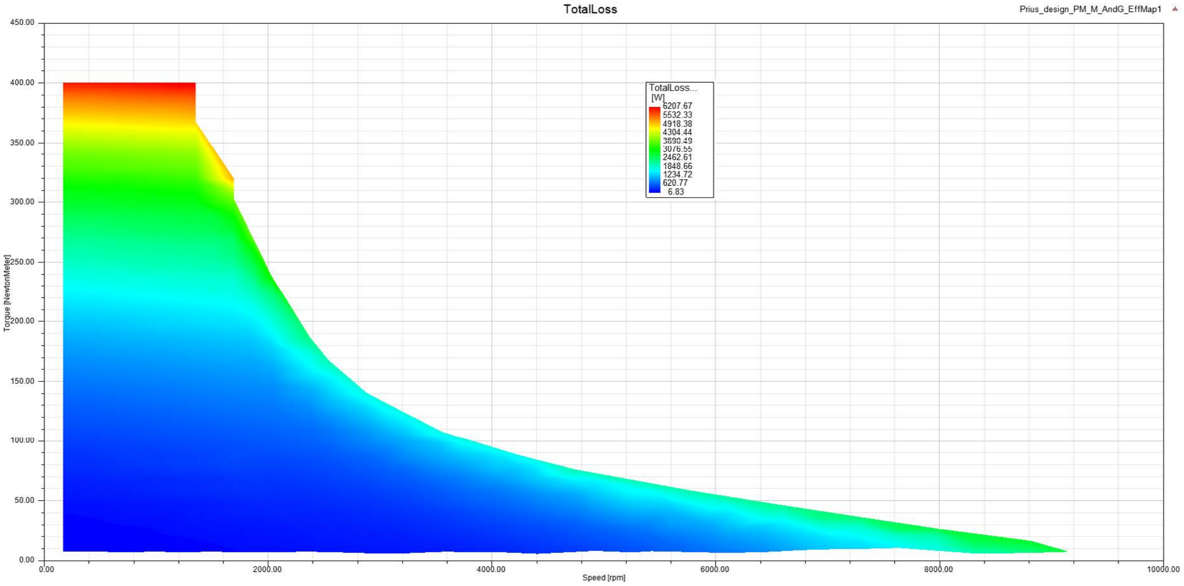


Figure 8. Total loss PM

Conclusion

ANSYS Maxwell is the ideal tool to perform an automated, highly scalable simulation of motors and to evaluate their performance by analyzing motor designs in many practical operating scenarios. The advanced level of automation in ANSYS Maxwell enables optimization of machine design using efficiency maps as outputs. Engineers can change several design parameters (dimensions, material, etc.), perform what-if experiments, automatically generate efficiency maps, and then use the efficiency map outputs to make informed design decisions through optimization. ANSYS Maxwell is the ideal tool for designing and simulating machines and for generating automatic efficiency maps that provide deep insights into a machine's performance in various practical operating scenarios. These simulations cut down on the design cycles, save costs, and improve the motor's overall safety, reliability and performance in various operating conditions.

Authors

Vincent Delafosse, Manohar Raju, Dr. Marius Rosu and Mark Ravenstahl.

ANSYS, Inc.
Southpointe
2600 ANSYS Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com