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
- Extendible

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.
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 2-D 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, \( \gamma \), 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 \( (I_d, I_q) \) 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.

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 left) various speed profile characteristics; (top right) magnetic flux density distribution; (bottom center) efficiency map
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Figure 7. Machine performance characteristics: (top left) current map; (top right) voltage map; (bottom left) power factor map; (bottom right) torque ripple map