Efficiency Map of 100-kW PMSM Drive

Altair PSIM Application Note

Overview

The efficiency map of a motor drive system is important design information as it gives system engineers a picture of the overall efficiency of the drive and what operating point to operate at for maximum efficiency.

The generation of the efficiency map of a PMSM drive system, however, is a significant task. It involves comprehensive load testing of the complete PMSM drive system with a motor dynamometer. The workload, time, and cost prohibit such activity most times. It is particularly true for a large power size PMSM drive system. The alternative way to obtain the efficiency map of a large power PMSM drive system is often through simulation. The finite element analysis (FEA) based motor model with accurate motor control as well as with automated simulations is required to obtain the efficiency map of the complete PMSM drive system. The simulation setup of a motor control system for a FEA-based motor is a non-trivial task by itself, and the script programming is also required for the automation of simulations.

The Motor Control Design Suite and automation script features make this task considerably easier. Pre-built design templates are provided for FEA based motors from JMAG (in JMAG-RT format) and motor control functions. Based on minimum system specifications, the Motor Control Design Suite automatically designs all the controllers for speed and current loops with properly specified crossover frequencies and stability margins, and implements advanced control algorithms such as Maximum-Torque-Per-Ampere (MTPA) control, field weakening control, and Maximum-Torque-Per-Volt (MTPV) control. It will generate a complete system that is operational and ready to simulate *in minutes*. The script programming code can help to automate numerous simulations without users' intervention for generating efficiency data of the PMSM drive system.

This application note describes how to generate the efficiency map of a 100-kW PMSM motor drive system using the **PMSM (IPM) Drive (JMAG-RT)(torque control)** template and the script code **efficiency map - speed-torque limit** script code. Files for this application note can be found in the folder "Application Notes\Efficiency map of 100-kW PMSM Drive" in PSIM.

Please refer to a companion application note Control Design of 100-kW PMSM Drive (AN001).pdf for speed control design of the same motor.

In **PMSM (IPM) Drive (JMAG-RT)** template, the IPM motor is modeled in a JMAG-RT model. A JMAG-RT model is derived from JMAG finite element analysis. It delivers a very high level of fidelity and accuracy as compared to the actual motor, with all nonlinear effects (such as saturation, spatial harmonics) included.

Unlike the motor in the linear PMSM drive system, the JMAG-RT motor in this system is nonlinear, and d-axis and q-axis inductances are functions of the motor currents *Id* and *Iq*. The nonlinear inductances Ld and Lq are conveniently obtained from the JMAG-RT model in real time, and are fed back to various control blocks to achieve the optimal control performance.

The power losses of the PMSM motor including copper loss and core loss can be obtained from the JMAG-RT model, and the power loss of the drive including switching loss and conduction loss can also be obtained from IGBT thermal module during the simulation. Hence the PMSM drive system power loss and efficiency can be easily derived from the power losses of the PMSM and its drive.

System Specifications

The 100-kW PMSM is based on the JMAG-RT motor model PMSM RTML-034 available from https://www.jmag-international.com/modellibrary/034/). It has the following parameters:

Model:	100k_D_C_IV	Height:	89 mm
Model Name:	PMSM	Magnet:	Neodymium sintered
Max. Power:	100 kW	Mass:	83.55 kg
Voltage/Current:	500 Vdc/200 A	Max. Motor Current:	283 A
Number of Poles:	12	Average Torque:	178 N*m
Number of Slots:	18	Ld:	0.24 mH
Number of Phases:	3	Lq:	0.36 mH
Rotor:	IPM	Inductance:	0.19 mH
Stator (outside dia.):	400 mm	Torque Constant:	0.627 N*m/A
Stator (inside dia.):	260 mm	Max. Speed:	9000 rpm
Stator:	Distributed winding	Inertia:	0.198 Kg*m^2

A 3-phase inverter with a 500-V dc bus and 283A current will be used to drive the motor.

## Step-by-Step Design Procedure

Several major steps are needed in order to derive the efficiency map of a PMSM drive system using the Motor Control Design Suite:

- Create an operational torque control system for the PMSM motor drive.
- Use the thermal module of the inverter to obtain the IGBT power loss, and add efficiency calculation.
- Run the script code to sweep the speed and torque and automatically simulate the motor drive at different operating points and obtain the efficiency map of the drive system.
- Plot the efficiency map contour.

Follow the steps below to perform the efficiency map generation.

**Step 1:** Launch the Design Suite template.

In PSIM, go to **Design Suites** >> **Motor Control Design Suite**, and select **PMSM (IPM) Drive (JMAG-RT)(torque control)**. Choose the folder to unpack the files. The template will be loaded to PSIM as shown below.
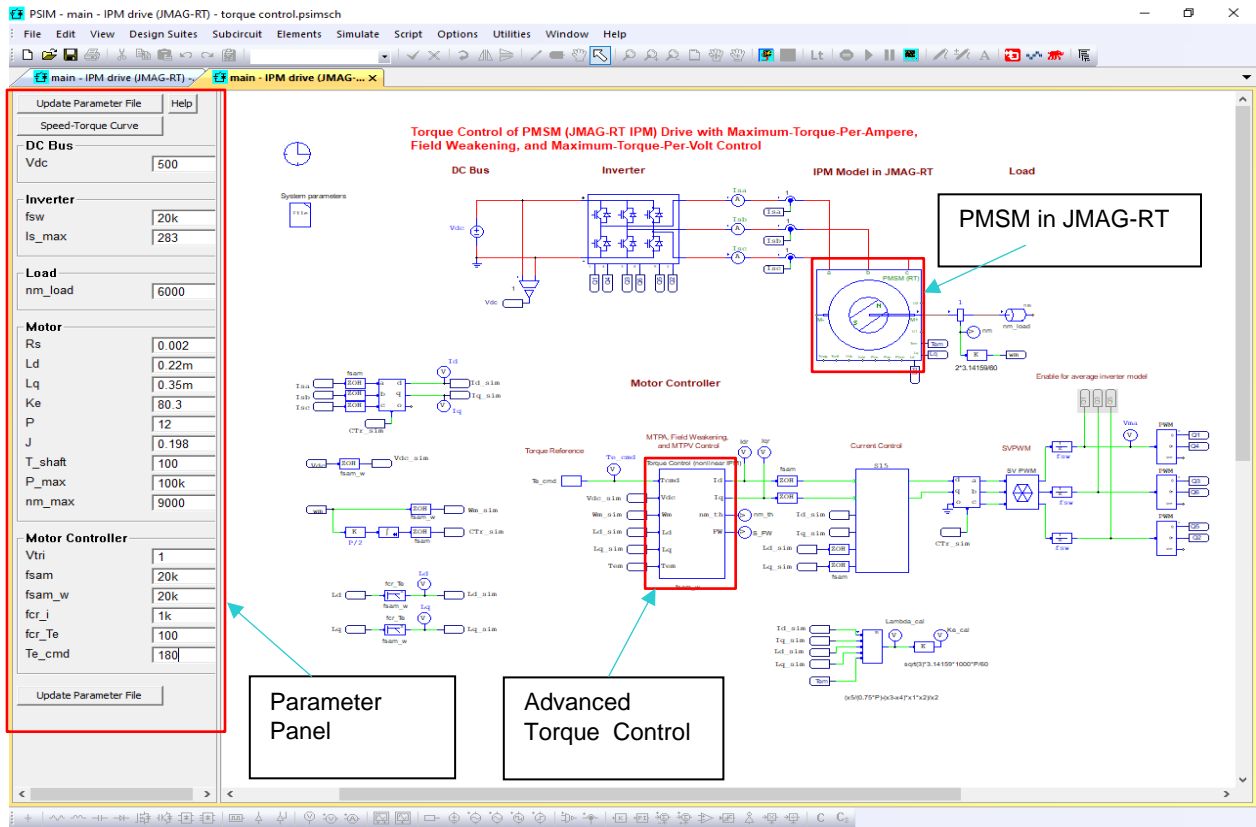
The Input Parameter Panel of the template and the PMSM block in the JMAG-RT model are highlighted in red. The advanced Torque Control block (also highlighted in red) includes MTPA, field weakening, and MTPV control all in one.

Step 2: Load the JMAG-RT model file.

Double click on the PMSM block. The following dialog menu will appear:
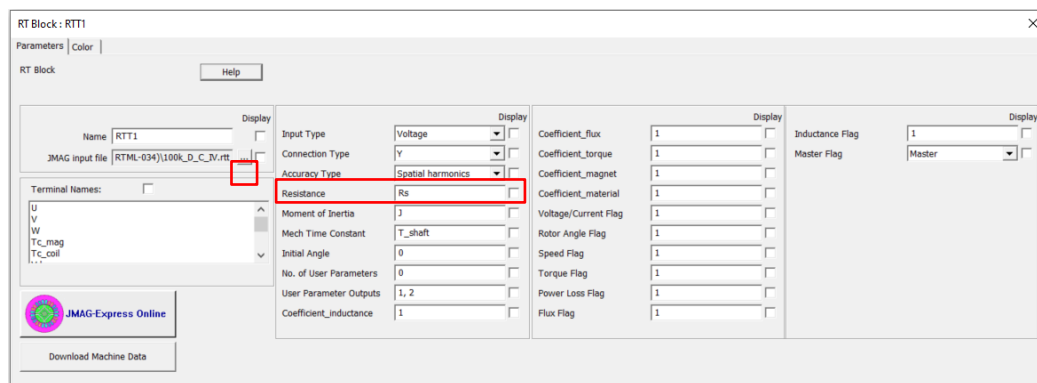
Click on the Browse button (highlighted in red above). Select and load the correct JMAG-RT file for the 100-kW PMSM, as shown below:
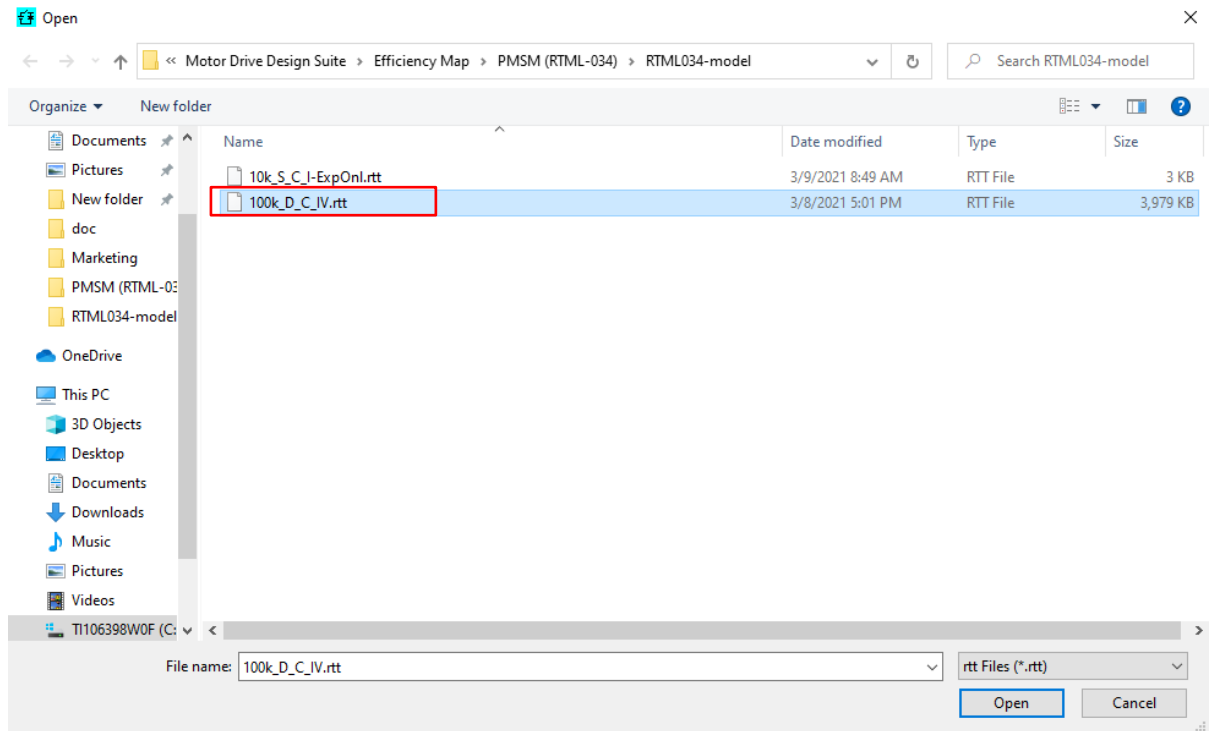
For this JMAG-RT model, the spatial harmonics model is available. Set the **Accuracy Type** to *Spatial Harmonics* to take into account the spatial harmonics effect.

Step 3: Enter system parameters.

Enter parameters of DC Bus, Inverter, Load, Motor, and Motor Controller in the Parameter Panel based on design requirement, operation conditions, and motor parameters, as shown below:

DC Bus:	
Vdc (operating dc bus voltage):	500
Inverter	
fsw (switching frequency):	20k
Is_max (maximum inverter current):	283
Load:	
Nm_load (load speed):	6000
Motor:	
Rs (stator resistance):	0.002
Ld (d-axis inductance):	0.22m
Lq (q-axis inductance):	0.35m

Ke (back EMF constant):	80.3
P (number of poles):	12
J (moment of inertia):	0.198
T_shaft (shaft time constant):	100
P_max (maximum power):	100k
nm_max (maximum speed):	9000
Motor Controller:	
Vtri (PWM carrier amplitude):	1
fsam (current loop sampling frequency):	20k
fsam_w (speed loop sampling frequency):	20k
fcr_i (current loop crossover frequency):	2k
fcr_Te (torque loop crossover frequency):	200
Te_cmd (torque command):	160

One needs to decide the proper values of the switching frequency fsw, the sampling frequency fsam of the current loop, and the sampling frequency fsam_w of the speed loop. One also needs to decide the crossover frequencies fcr_i and fcr_Te of the current loop and the torque loop. Typically, fcr_i should be roughly fsam/10 or less, and fcr_Te should be roughly fcr_i/10 or less.

For this motor, considering the power level of 100 kW, we choose fsw, fsam, and fsam_w to be 20 kHz, fcr_i to be 2kHz, and fcr_Te to be 200 Hz.

Click on the button **Update Parameter File** to update the system parameters for simulation.

Step 4: Run simulation to validate a functional and stable motor drive system.

Once the parameter file is updated, it's ready to run the simulation. It is important that the system is functionally stable and has reached the steady state.

Again, one may need to adjust fsw, fsam, fsam_w, fcr_i, fcr_Te, and the simulation time step to achieve the desired performance. Also, adjust the simulation time so that motor torque and system efficiency reach the steady state.

One key simulation waveform to watch is the modulation signal Vma at the input of the PWM block. The waveform Vma should not be severely out of the range of the carrier wave.

Simulation results from this step are shown below.
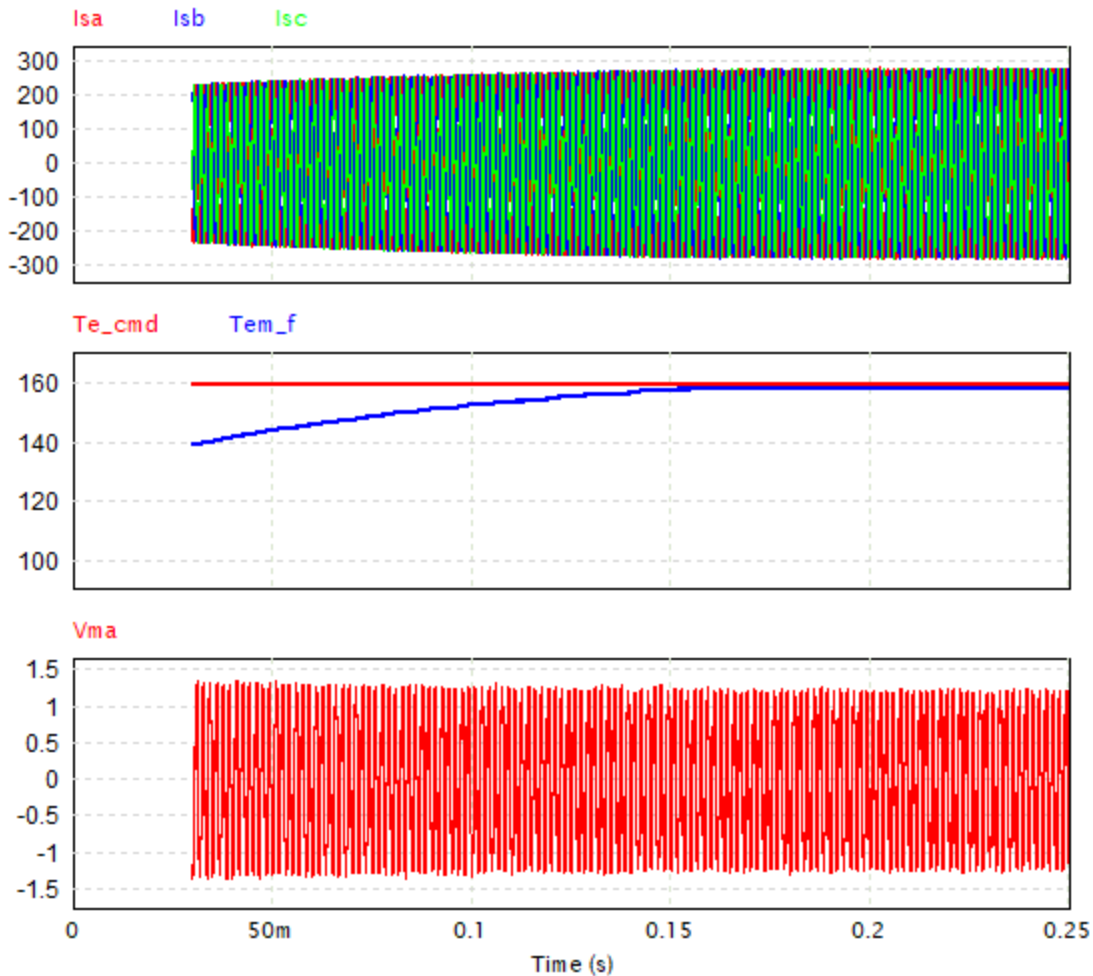
The waveforms show the start-up transient of the 100-kW IPM drive from 0 to 160 Nm at the speed of 6000 rpm.

The traces in the first window are the motor currents.

The traces in the second window are the torque reference and the actual torque. It reaches 160 Nm around 0.2 s.

The trace in the third window is the modulation signal Vma.

Step 5: Run simulation again to validate system efficiency calculation.

Make changes to the simulation schematics highlighted in red shown below and run the simulation:

- Replace the inverter with an inverter from the Thermal Module for loss calculation.
- Add circuit to obtain motor power loss from the JMAG-RT motor model.
- Add circuit to obtain motor torque from the JMAG-RT motor model.
- Add efficiency calculation circuit to obtain the motor drive system efficiency.
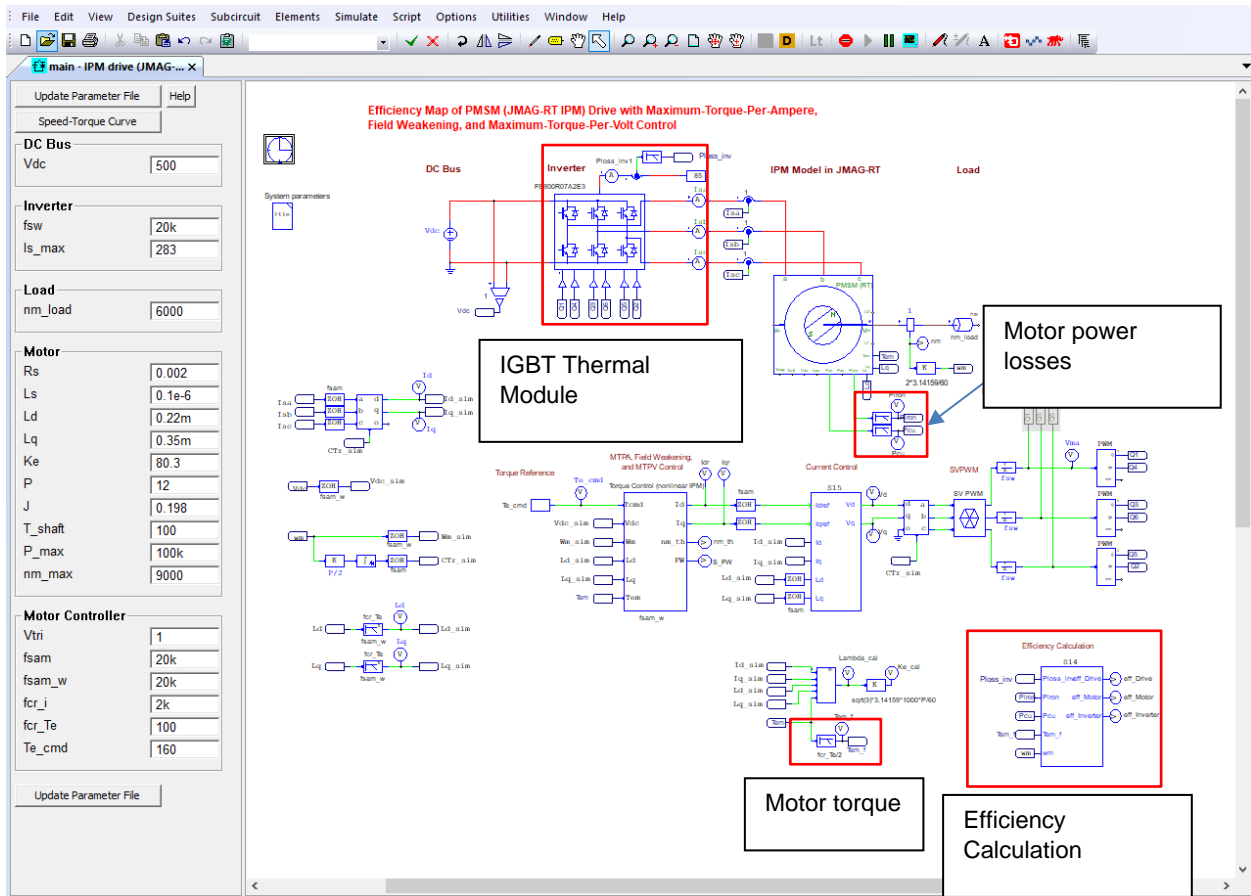
In this example, we select the Infineon HybridPACK 2 IGBT FS800R07A2E3 for the inverter, and two HybridPACK 2 connected in parallel are used.

The motor copper loss and iron loss are obtained from the JMAG-RT model. A low-pass filter is used at each power loss output to smooth out the waveform.

The motor developed torque is also obtained from the JMAG-RT model. This torque contains a significant amount of spatial harmonics, and a low-pass filter is used to smooth out the waveform.

The efficiency calculation subcircuit is given in the PSIM folder "Application notes\Efficiency Map of 100-kW".
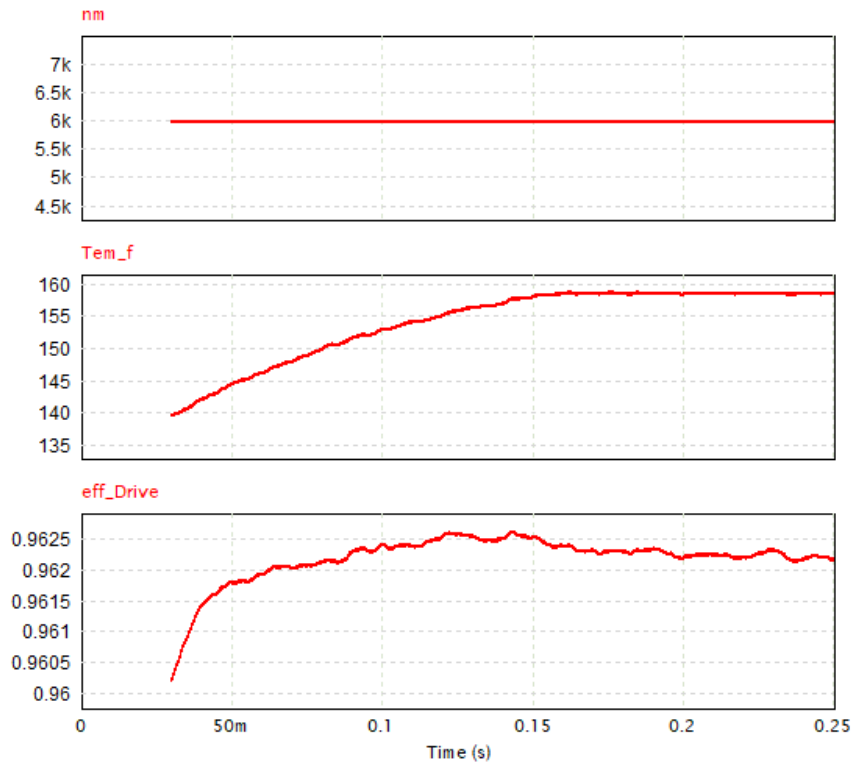
Simulation results from this step are shown below.

The waveforms show the steady state of the 100-kW IPM drive.

The trace in the first window is the motor speed (6000 RPM).

The trace in the second window is the steady state motor torque of around 160 Nm.

The trace in the third window is the steady state system efficiency of around 96.2%.

Step 6: Run automated simulations with the script code and plot the efficiency map.

After the simulation is fully set up and ready to generate the efficiency map, one can run simulations by sweep the torque command and the load speed, and record the system efficiency. In this example, Te_cmd is set as 20, 40, …, 200 Nm (10 points), and nm_load is set as 1000, 2000, …, 9000 RPM (9 points). For this example, a total of 90 simulations (i.e. 9x10) are required to capture the complete system efficiency data over the entire speed-torque range, and this is a big and time-consuming task.

PSIM's script function can be used to automate the process. A script code "efficiency map – speed-torque limit.script" is prepared to run all the simulations, record the efficiency map data (system efficiency **eff_Drive**, motor efficiency **eff_motor** and inverter efficiency **eff_inv** vs. the speed nm and torque Tem), and create three Matlab m files for plotting the contour maps of the motor, inverter and drive system efficiencies in the Matlab software.
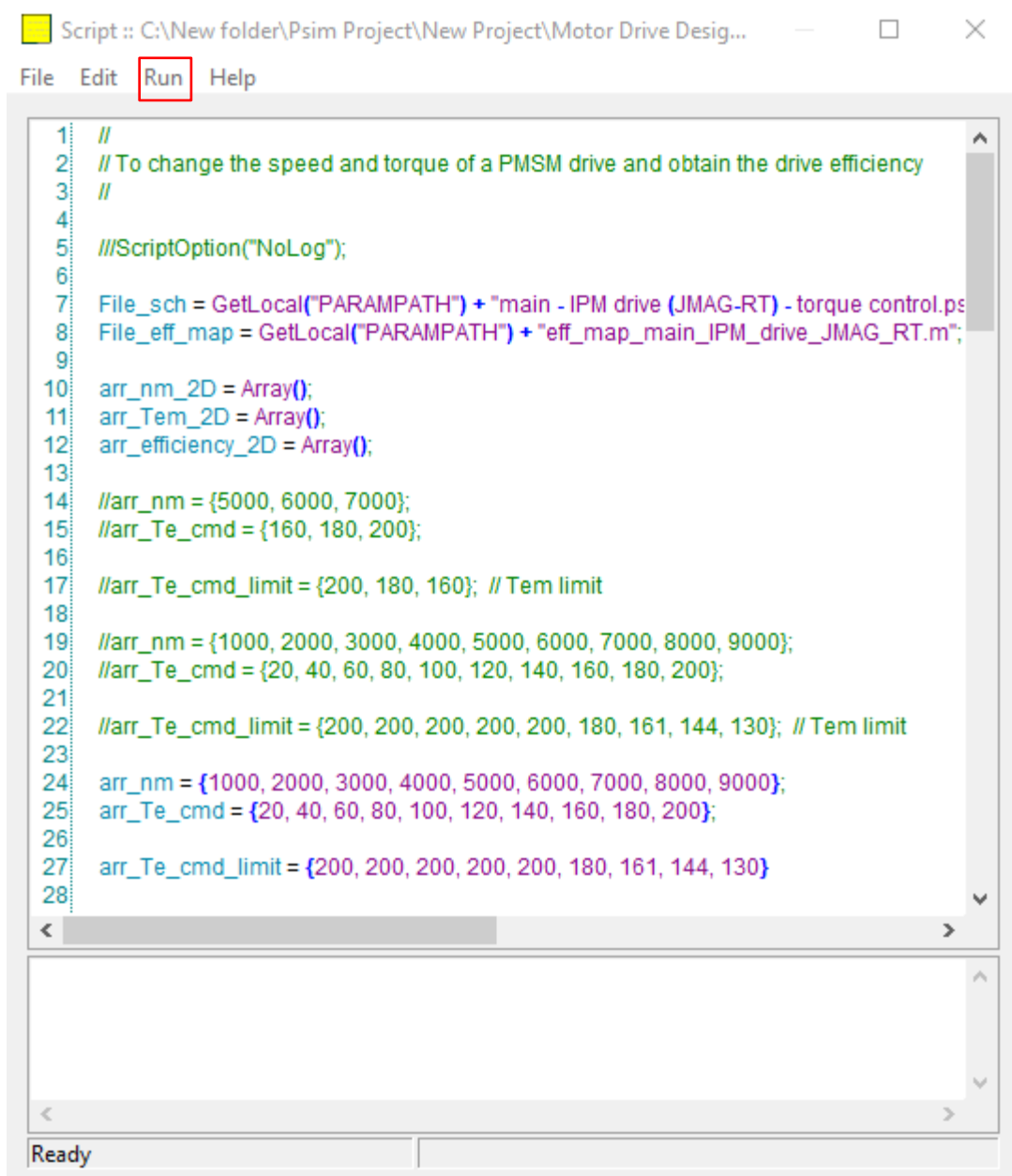
Before running the script code, one needs to disable the speed and torque commands from the parameter file in the simulation schematic as shown below:

```
parameters-main.txt                                          ×

 File   Edit   Help

Parameter file name

Name   Traction

File    fficiency Map\PMSM (RTML-034)\main - IPM drive (JMAG-RT) - torque control\parameters-main.txt

21   Is_max = 283         // maximum inverter current (peak), in A
22
23   //------------- Load -----------------
24
25   //nm_load = 6000       // load speed, in rpm
26
27   //------------- Motor -----------------
28
29   Rs = 0.002           // stator winding resistance, in Ohm
30   Ls = 1E-07           // stator leakage indutance, in H
31   Ld = 0.00022         // d-axis inductance at rated conditions, in H
32   Lq = 0.00035         // q-axis inductance at rated conditions, in H
33
34   Ke = 80.3            // back EMF constant Vpk/krpm
35   P = 12               // number of poles
36
37   J = 0.198            // moment of inertia, in kg-m^2
38   T_shaft = 100        // shaft time constant, in sec.
39
40   P_max = 100000       // maximum motor power, in W
41   nm_max = 9000        // maximum motor speed, in rpm
42
43   //------------- Motor Controller -----------------
44
45   Vtri = 1             // PWM carrier peak amplitude
46
47   fsam = 20000         // current loop sampling Freq
48   fsam_w = 20000       // torque loop sampling Freq
49
50   //Current loop Control parameters entered
51   fcr_i = 2000         //current loop crossover frequency
52
53   // Torque loop Control parameters entered
54   fcr_Te = 200         // torque loop crossover frequency
55
56   //Te_cmd = 160         // reference torque, in N*m
57
58
```

To run the script, load the script "efficiency maps - speed-torque limit.script" into PSIM, and select
**Run** >> **Run Script** as shown below.

After automated simulations are completed, three Matlab m-files "efficiency_map_drive.m", "efficiency_map_motor.m", and "efficiency_map_inverter.m" that contain the efficiency map data for the drive system, motor, and inverter respectively will be created. Launch Matlab, and load and run the m-files. The efficiency maps for this example are shown below (top left: motor; top right: inverter; bottom: drive system).

From these efficiency maps, one can conclude that if the PMSM motor is operated in the region of 1500-2500 rpm and 120-185 N*m, or 5000-9000 rpm and torque along the limit of the speed-torque curve, it achieves the highest efficiency. But the highest efficiency region for the inverter is when speed is 5000 to 9000 rpm, and torque along the limit of the speed-torque curve. Overall, for the drive system, the highest efficiency region is when the speed is 5000 to 9000 rpm, and torque is along the limit of the speed-torque curve.
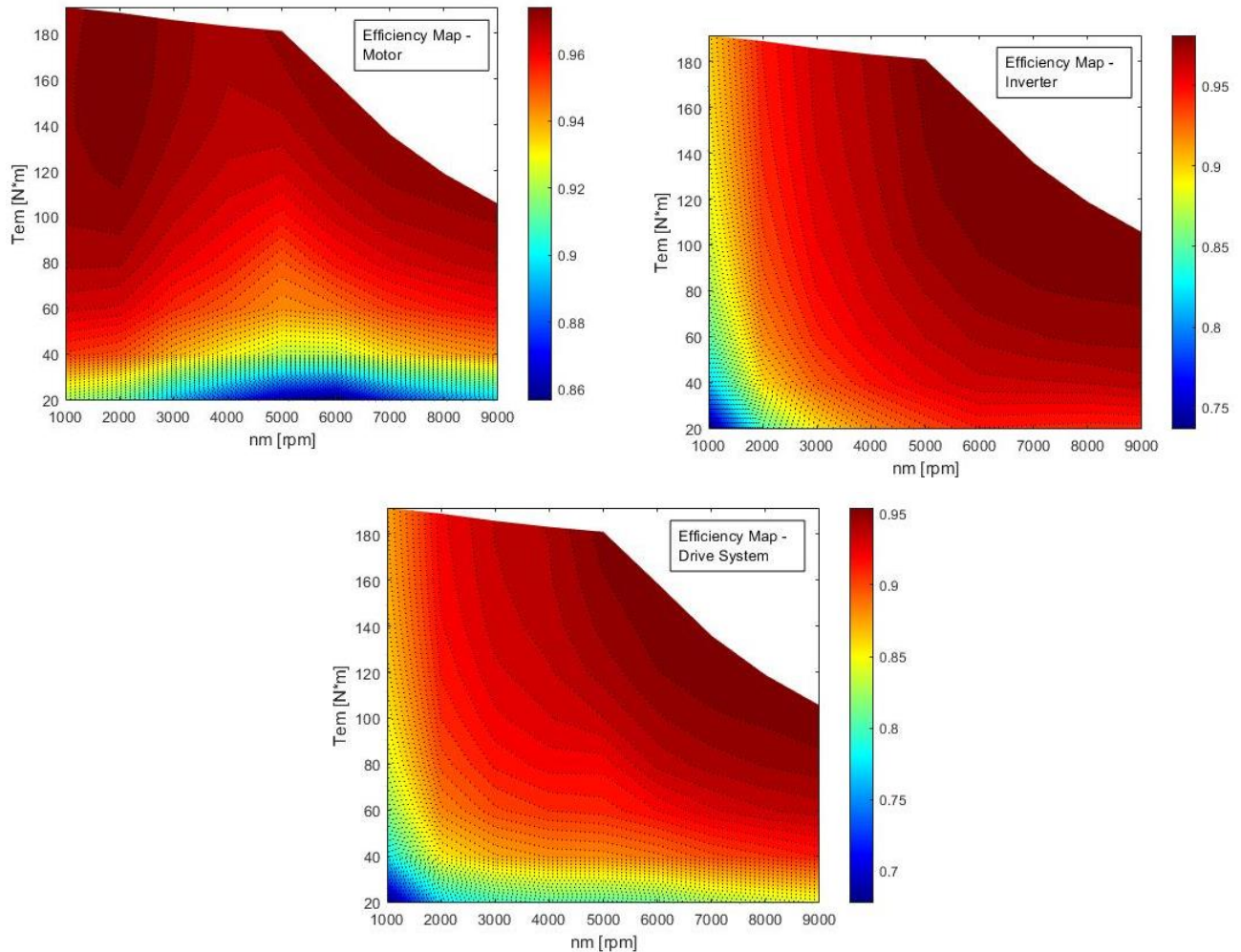
To generate an efficiency map with finer resolution, more speed and torque points can be selected.

Conclusions

With the Motor Control Design Suite, JMAG-RT motor model, and the script function in PSIM, the process of generating the efficiency map of a motor drive system, which is difficult, tedious, and time-consuming, is made considerably easier. This greatly helps motor design engineers in evaluating the motor performance in a motor drive environment, and helps system engineers in determining the optimum operation of the motor drive system.