

Application Note

AN001-01

Control Design of 100-kW PMSM Drive

March 2021

1. Overview

Control loop design of a PMSM drive is a non-trivial task. It involves design of the inner current loop and outer speed loop. In addition, motor nonlinearity and other factors, such as switching and sampling frequencies and motor and drive efficiencies, must be considered. Also, to achieve the optimum performance, advanced control algorithms need to be developed and implemented.

The Motor Control Design Suite in PSIM makes this task considerably easier. Pre-built design templates are provided for linear and nonlinear PMSM and induction machines (IM) with sensed or sensorless control. Based on minimum system specifications, the Motor Control Design Suite automatically designs all the controllers for speed and current loops with proper specified crossover frequencies and stability margins and with 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*.

This application note describes how to design an optimized motor drive for a 100-kW PMSM using the **PMSM (IPM) Drive (JMAG-RT)** template. Files for this application note can be found in the folder “Application Notes\Control Design of 100-kW PMSM Drive” in PSIM.

Please refer to a companion application note [Efficiency Map of 100-kW PMSM Drive \(AN002-01\).pdf](#) for efficiency map generation of the motor drive system using this motor.

In this 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 I_d and I_q . The nonlinear inductances L_d and L_q 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.

2. 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	L_d :	0.24 mH
Number of Phases:	3	L_q :	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

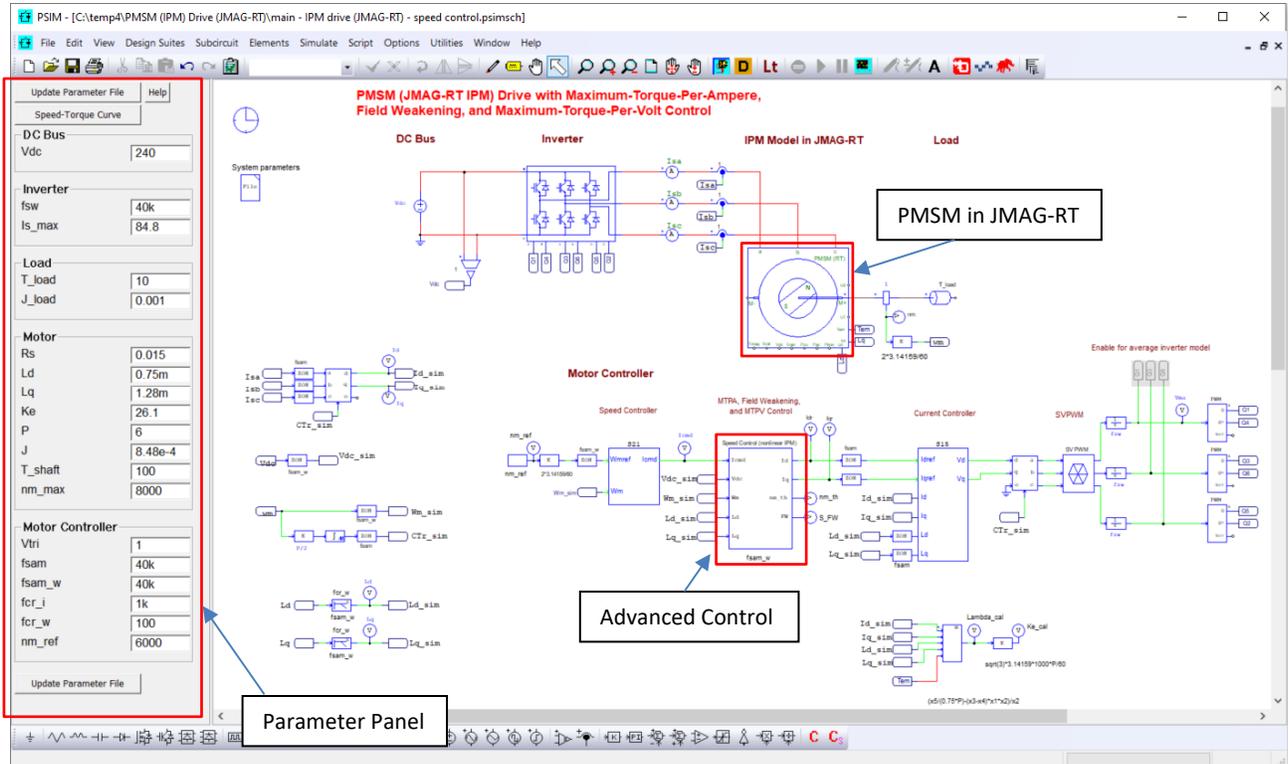
A 3-phase inverter with a 500-V dc bus and 283A current will be used to drive the motor.

3. Step-by-Step Design Procedure

Follow the steps below to perform the design.

Step 1: Launch the Design Suite template.

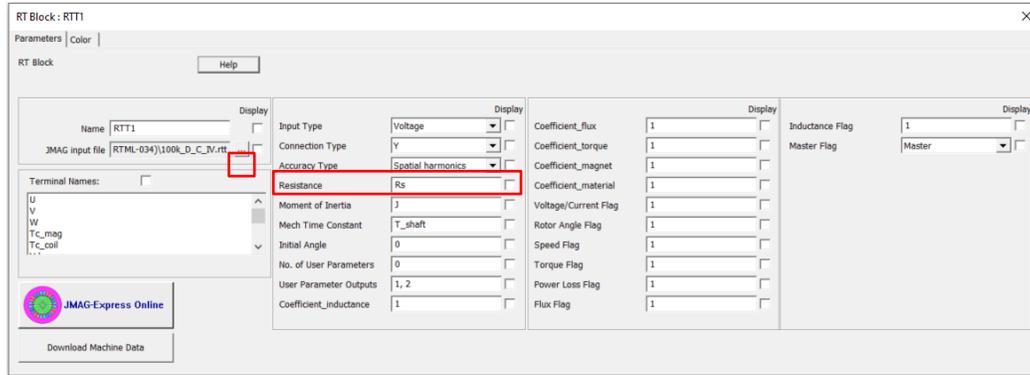
In PSIM, go to **Design Suites >> Motor Control Design Suite**, and select **PMSM (IPM) Drive (JMAG-RT)**. Choose the folder to unpack the files. The template will be loaded to PSIM as shown below.



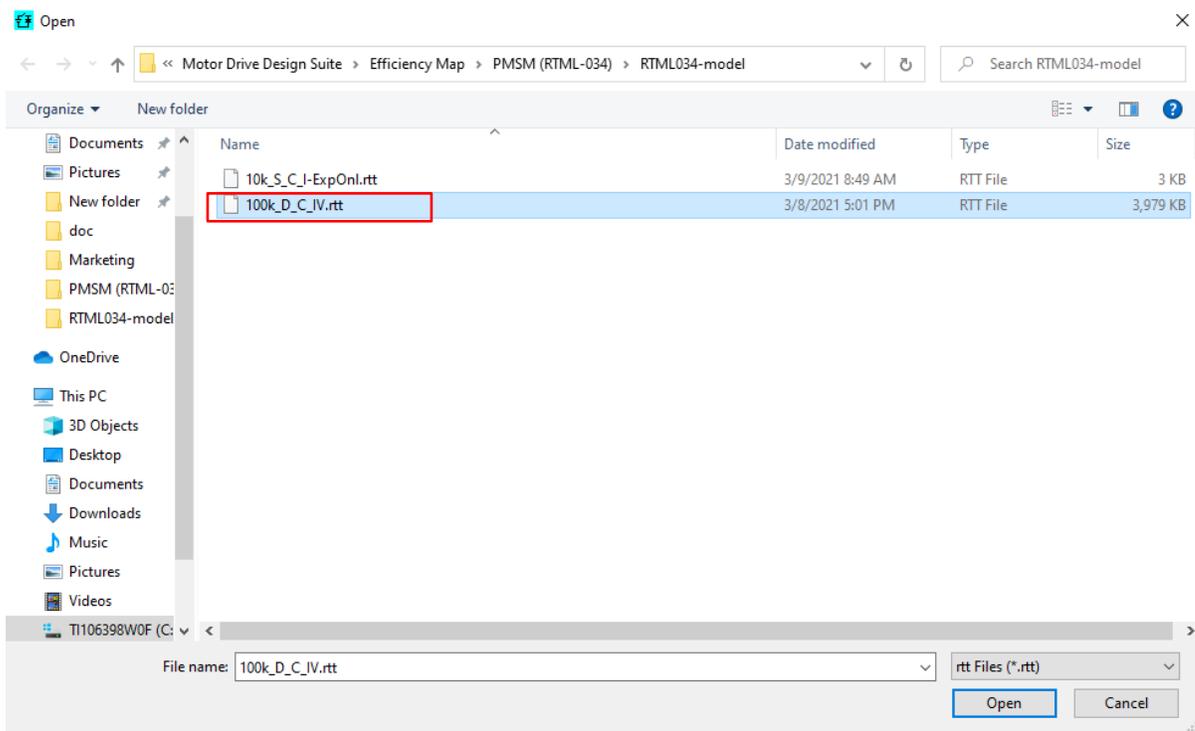
The Input Parameter Panel of the template and the PMSM block in the JMAG-RT model are highlighted in red. The advanced Speed Control block (also highlighted in red) includes MTPA, field weakening, and MTPV control all in one.

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

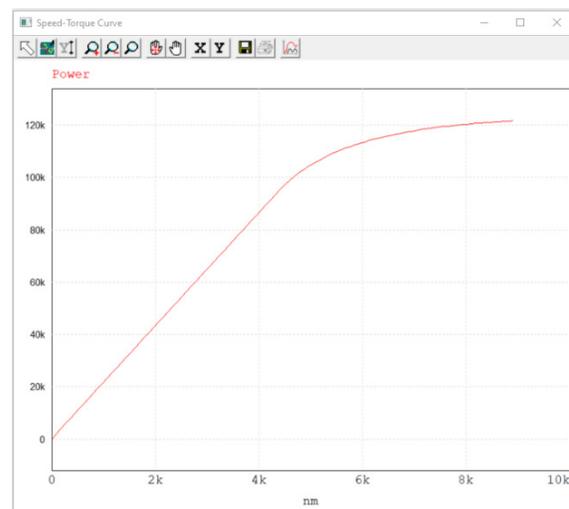
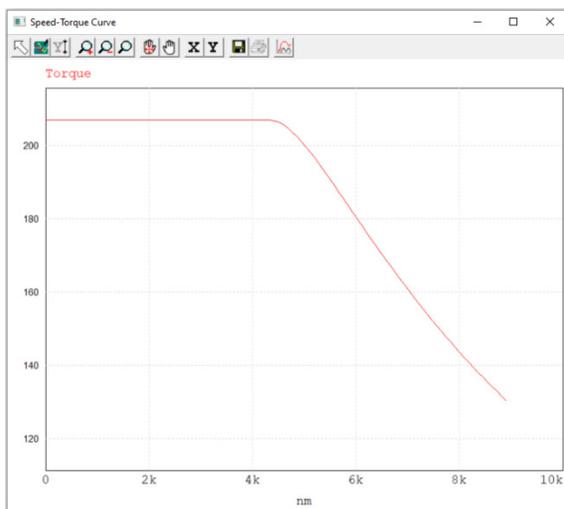
Load:	
T_load (load torque):	25
J_load (load moment of inertia):	0.001
Motor:	
Rs (stator resistance):	0.002
Ld (d-axis inductance):	0.22m
Lq (q-axis inductance):	0.35m
Ke (back EMF constant):	80.3
P (number of poles):	12
J (moment of inertia):	0.198
T_shaft (shaft time constant):	100
nm_max (maximum 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):	1k
fcr_w (speed loop crossover frequency):	100
nm_ref (speed reference in rpm):	6000

The stator resistance R_s of 0.002 Ohm is obtained from the JMAG-RT model.

One needs to decide the proper values of the switching frequency f_{sw} , the sampling frequency f_{sam} of the current loop, and the sampling frequency f_{sam_w} of the speed loop. One also needs to decide the crossover frequencies f_{cr_i} and f_{cr_w} of the current loop and the speed loop. Typically, f_{cr_i} should be roughly $f_{sam}/10$ or less, and f_{cr_w} should be roughly $f_{cr_i}/10$ or less.

For this motor, considering the power level of 100 kW, we choose f_{sw} , f_{sam} , and f_{sam_w} to be 20 kHz, f_{cr_i} to be 1kHz, and f_{cr_w} to be 100 Hz.

Once all input parameters are entered, click on the button **Speed-Torque Curve** to see speed-torque and speed-power curves of the drive based on the specified parameters, as shown below.



These curves give a very quick glance of the operation boundary of the drive before running any simulation. For example, in this case, the maximum torque is around 210 N*m, and the base speed (the rotor speed where field weakening starts) is around 4400 rpm. One can also change the dc bus voltage and the inverter current, and see how the change affects the torque and power of the drive.

Click on the button **Update Parameter File** to update the system parameters for simulation. The parameter file contains the parameters entered by the user and the ones calculated by the Design Suite, as shown below.

The screenshot displays the PSIM Design Suite interface. On the left is the 'Update Parameter File' panel with sections for DC Bus, Inverter, Load, Motor, and Motor Controller. On the right is a text editor window titled 'parameters-main.txt' showing the generated parameter file. A red box highlights the Motor Controller section in both the panel and the text file.

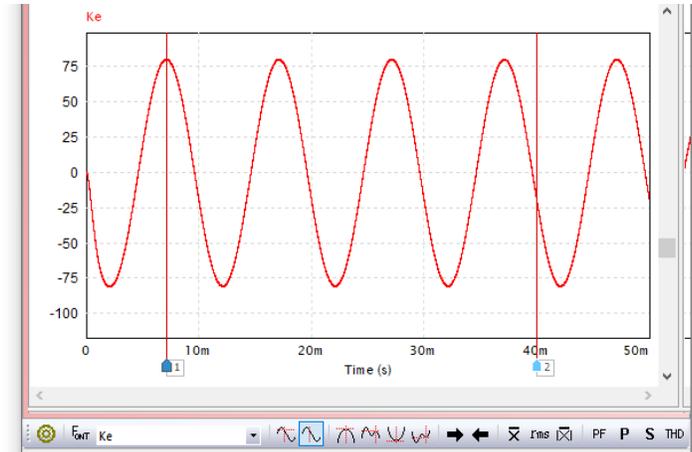
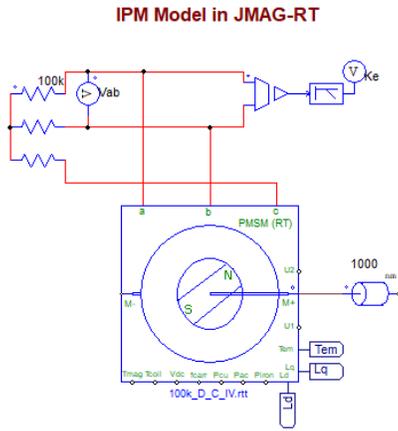
Section	Parameter	Value
DC Bus	Vdc	500
	Inverter	
	fsw	20k
Load	T_load	25
	J_load	0.001
	Motor	
Rs	0.002	
Ls	0.1e-6	
Ld	0.22m	
Lq	0.35m	
Ke	80.3	
P	12	
J	0.198	
T_shaft	100	
nm_max	9000	
Motor Controller		
Vtri	1	
fsam	20k	
fsam_w	20k	
fcr_i	1k	
fcr_w	100	
nm_ref	6000	

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62
63 //----- Inverter -----
64
65 Vs_max = 288.6751345948129 // maximum inverter ac voltage (phase peak)
66
67 //----- Motor -----
68
69 Te_max = 206.8099246708683 // calculated maximum torque based on current limit Ismax
70 K_TA = 0.7307771189783333 // torque constant, in N*m/A
71
72 //----- Motor Controller -----
73
74 // d-axis control loop
75 K_d = 25.13272 // PI gain
76 T_d = 499.9999999999999 // PI time constant
77
78 // q-axis control loop
79 K_q = 25.13272 // PI gain
80 T_q = 500.2531847133758 // PI time constant
81
82 PM_i = 72.55940461622478 // current loop phase margin, in deg.
83
84 // Speed control loop
85 K_w = 171.0990653002467 // PI gain
86 T_w = 0.01591550775244382 // PI time constant
87
88 PM_w = 78.57888009774129 // speed loop phase margin, in deg.
89
  
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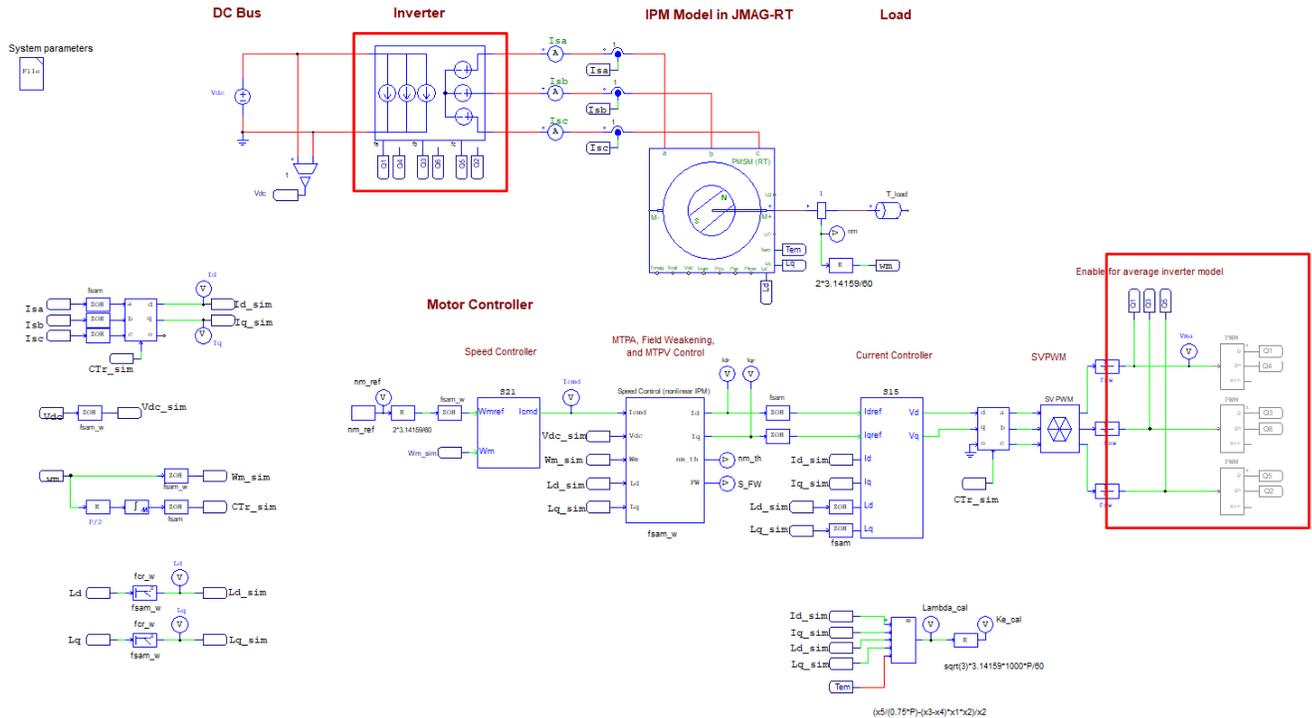
One key feature of the Design Suite is that parameters of the current loop and the speed loop controllers are calculated automatically, saving users a lot of time and effort in designing the controllers themselves. If any of the parameters in the Parameter Panel are changed, one **must** click on **Update Parameter File** again to update the parameter file. Otherwise the parameters will not be updated.

If the back EMF constant K_e is not available, or if one wants to double check the value, we provide a simple open-circuit test file **IPM drive (JMAG-RT) - back-emf test.psim**, as shown below. This circuit runs the motor at 1000 rpm. The peak line-to-line voltage will give the value of K_e . For this motor, $K_e=80.3$ Vpk/krpm.



Step 4: Run simulation with the inverter average model.

Once the parameter file is updated, it's ready to run simulation. We suggest to run simulation first using the inverter average model as shown below. Changes to the circuit are highlighted in red.



Since the initial values of f_{sw} , f_{sam} , f_{sam_w} , f_{cr_i} , and f_{cr_w} may not work at the first try, using the average model will exclude the effect of switching and focus on getting the control loops to work first. Also, simulation with the average model is much faster.

One may need to adjust f_{sam} , f_{sam_w} , f_{cr_i} , f_{cr_w} , and the simulation time step to achieve the desired performance.

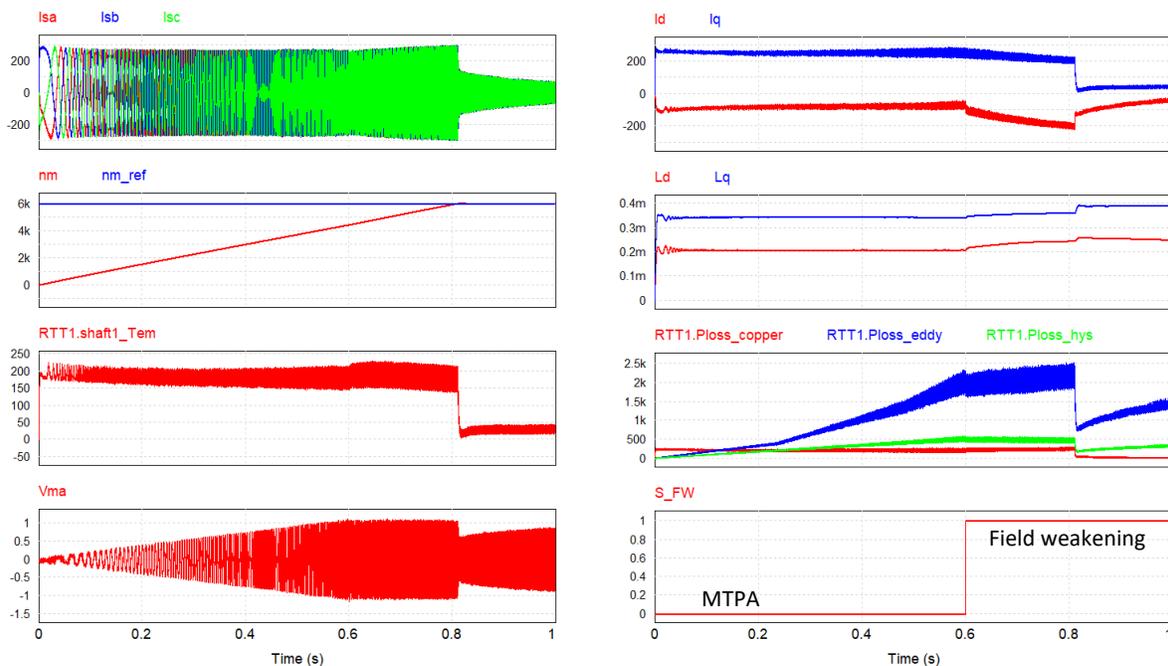
Step 5: Run simulation with the inverter switching model.

Once the system works with the inverter average model, change the inverter model back to the switch model to validate the design.

Again, one may need to adjust f_{sw} , f_{sam} , f_{sam_w} , f_{cr_i} , f_{cr_w} , and the simulation time step to achieve the desired performance.

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

Simulation results from this design are shown below.



The waveforms show the start-up transient of the 100-kW IPM drive from 0 to 6000 rpm.

The traces in first window on the left are the motor currents.

The traces in second window on the left are the speed reference and the actual speed. It reaches 6000 rpm around 0.8 s.

The trace in third window on the left is the motor torque. It drops from 200 N*m to 25 N*m (load torque) when the speed reaches the reference value. The torque ripple due to spatial harmonics is clearly visible.

The trace in fourth window on the left is the modulation signal V_{ma} .

The traces in first window on the right are the i_d and i_q currents.

The traces in second window on the right are the L_d and L_q inductances.

The traces in third window on the right are the motor copper loss $Ploss_copper$, eddy current loss $Ploss_eddy$, and hysteresis loss $Ploss_hys$.

The trace in the fourth window on the right is the operation mode. Before 0.6 s, the drive operates in MTPA control. After 0.6 s, the drive operates in field weakening control.

As clearly seen, the motor inductances L_d and L_q vary with the currents I_d and I_q . It is important to point out that it is necessary to implement nonlinear control in dq current control loops and PMSM controller where L_d and L_q (both varied with I_d and I_q) are fed back to these controllers so that the dynamic nature of L_d and L_q is accounted for in the control loops to achieve better performance.

By replacing the inverter with the inverter module from the Thermal Module, one can obtain device switching losses and junction temperature as well. Together with the power loss of the motor obtained from the JMAG-RT motor model, one can evaluate the power loss and efficiency of the entire motor drive system.

4. Conclusions

With the Motor Control Design Suite and the JMAG-RT motor model, one can quickly set up and simulate a PMSM drive system that takes into account all the nonlinearities of a real motor. This greatly helps motor design engineers and control engineers in evaluating the motor performance in a motor drive environment, and helps hardware engineers in designing and designing and sizing the inverter.