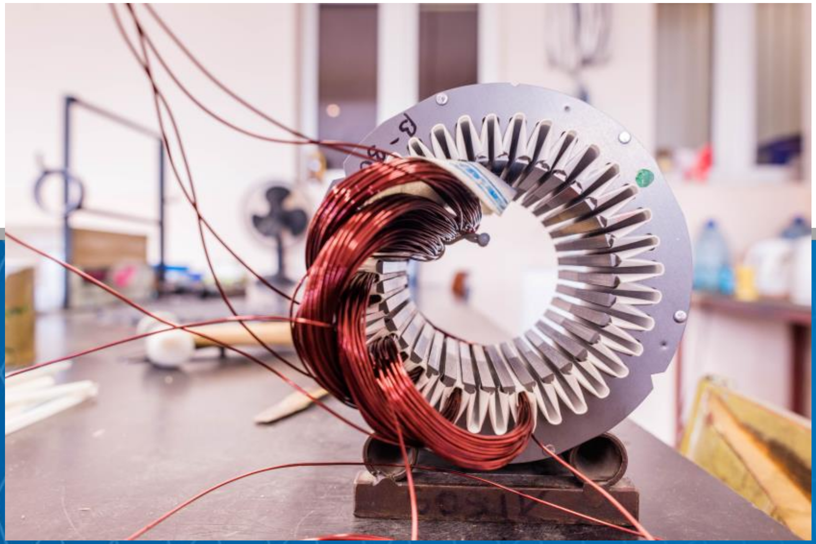
PMSM Model Fidelities and Their Implementation in Simulation



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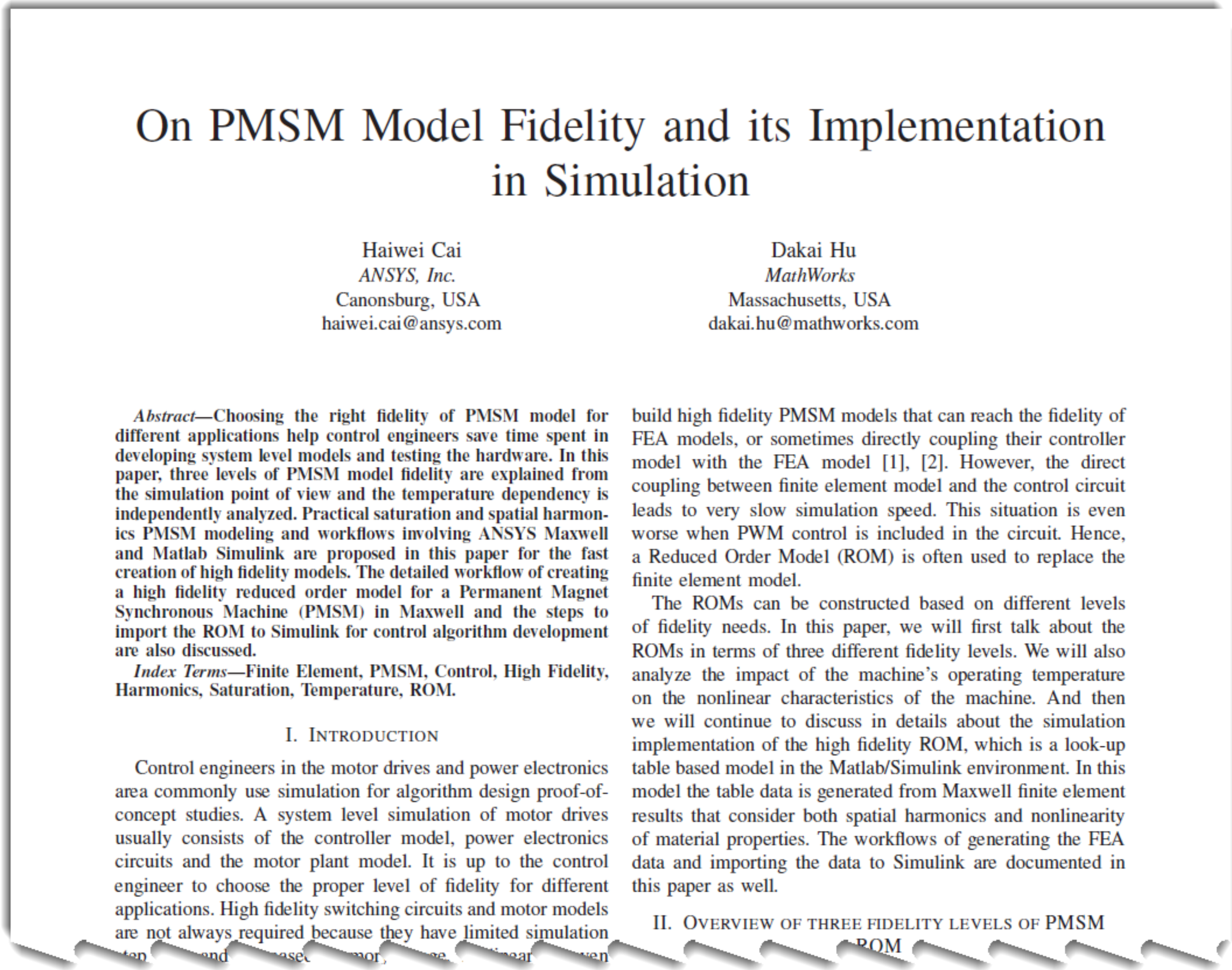
MathWorks Sr. Application Engineer
5/27/2020



On PMSM Model Fidelity and its Implementation in Simulation

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***Abstract*—Choosing the right fidelity of PMSM model for different applications help control engineers save time spent in developing system level models and testing the hardware. In this paper, three levels of PMSM model fidelity are explained from the simulation point of view and the temperature dependency is independently analyzed. Practical saturation and spatial harmonics PMSM modeling and workflows involving ANSYS Maxwell and Matlab Simulink are proposed in this paper for the fast creation of high fidelity models. The detailed workflow of creating a high fidelity reduced order model for a Permanent Magnet Synchronous Machine (PMSM) in Maxwell and the steps to import the ROM to Simulink for control algorithm development are also discussed.**

***Index Terms*—Finite Element, PMSM, Control, High Fidelity, Harmonics, Saturation, Temperature, ROM.**

I. INTRODUCTION

Control engineers in the motor drives and power electronics area commonly use simulation for algorithm design proof-of-concept studies. A system level simulation of motor drives usually consists of the controller model, power electronics circuits and the motor plant model. It is up to the control engineer to choose the proper level of fidelity for different applications. High fidelity switching circuits and motor models are not always required because they have limited simulation

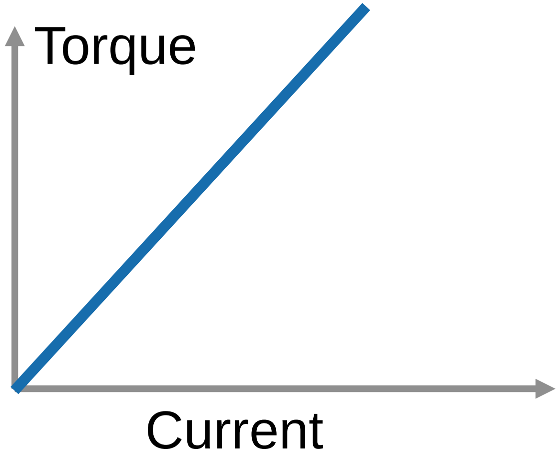
build high fidelity PMSM models that can reach the fidelity of FEA models, or sometimes directly coupling their controller model with the FEA model [1], [2]. However, the direct coupling between finite element model and the control circuit leads to very slow simulation speed. This situation is even worse when PWM control is included in the circuit. Hence, a Reduced Order Model (ROM) is often used to replace the finite element model.

The ROMs can be constructed based on different levels of fidelity needs. In this paper, we will first talk about the ROMs in terms of three different fidelity levels. We will also analyze the impact of the machine's operating temperature on the nonlinear characteristics of the machine. And then we will continue to discuss in details about the simulation implementation of the high fidelity ROM, which is a look-up table based model in the Matlab/Simulink environment. In this model the table data is generated from Maxwell finite element results that consider both spatial harmonics and nonlinearity of material properties. The workflows of generating the FEA data and importing the data to Simulink are documented in this paper as well.

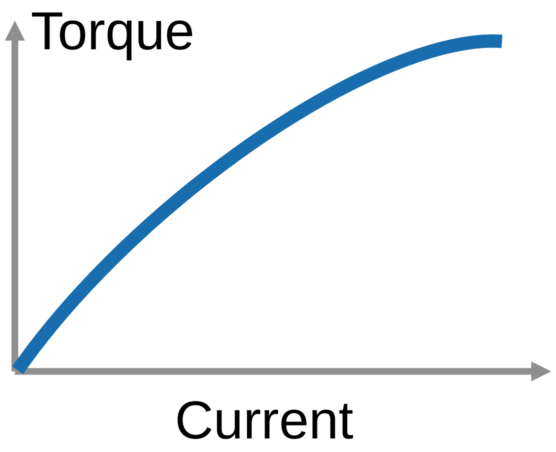
II. OVERVIEW OF THREE FIDELITY LEVELS OF PMSM ROM

H.Cai and D. Hu, "On PMSM Model Fidelity and its Implementation in Simulation" in 2018 IEEE Energy Conversion Congress and Exposition, Sep.2018. Portland, OR, USA.

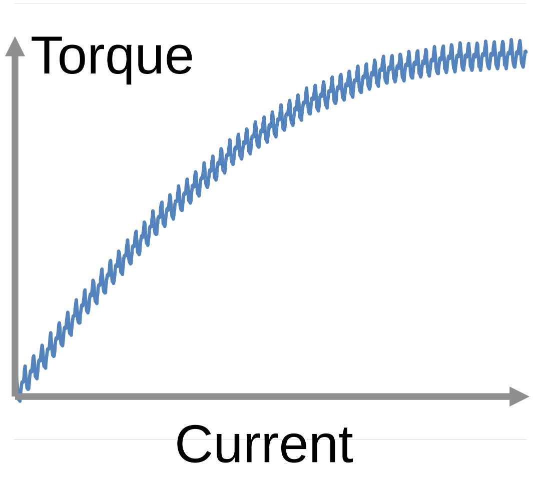
Three Levels of PMSM Model Fidelity



Lumped Parameter

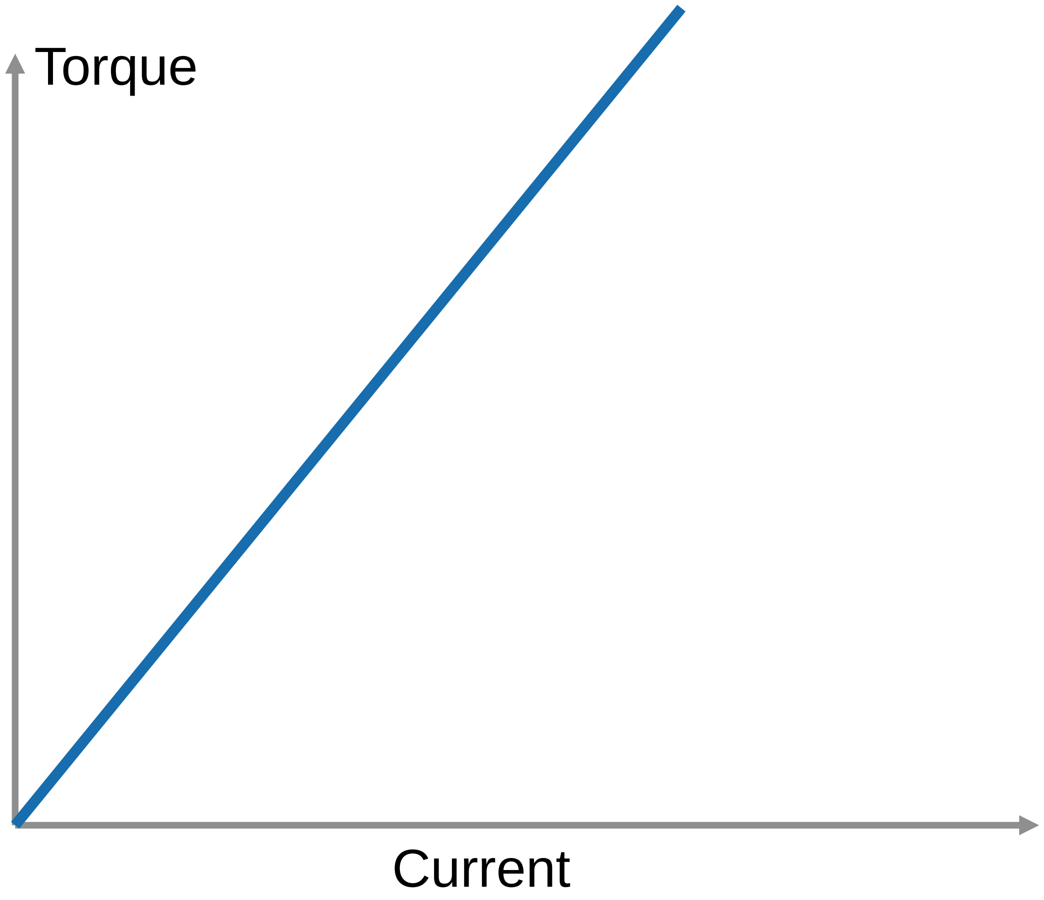


Saturation



Saturation +
Spatial Harmonics

Lumped-Parameter Model



Electrical Model

$$v_d = Ri_d - L_q p\omega_r i_q + L_d \frac{d}{dt} i_d$$

$$v_q = Ri_q + p\omega_r (L_d i_d + \lambda) + L_q \frac{d}{dt} i_q$$

$$\omega_e = p\omega_r$$

$$T_e = 1.5p\left[\lambda i_q + \left(L_d - L_q\right) i_d i_q\right]$$

$$T_e = K_t i_q \ \left(assumes\ round\ rotor, L_d = L_q\right)$$

Mechanical Model

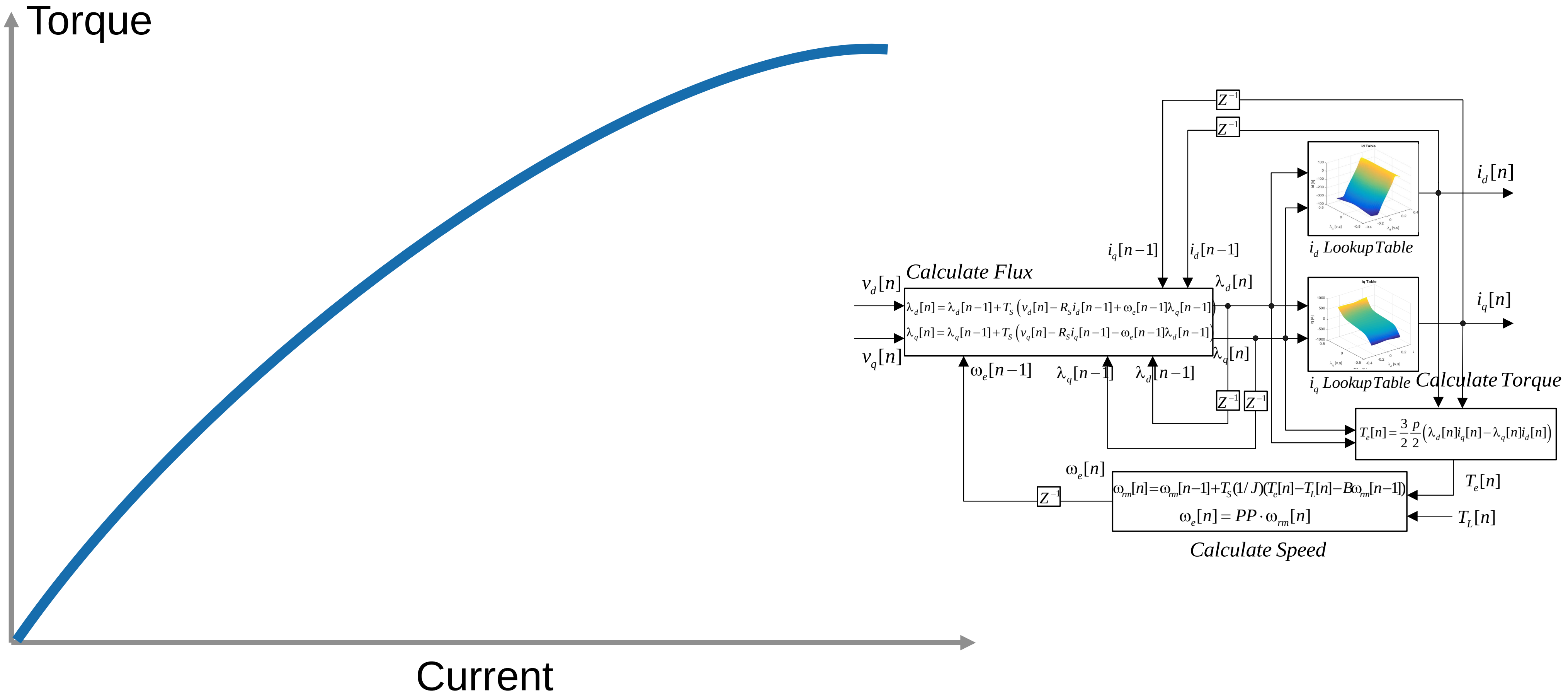
$$\frac{d}{dt}\omega_r = \frac{1}{H}\left(T_e - sgn(\omega_r)J_0 - b\omega_r - T_{load}\right)$$

How to Get Those Parameters ?

Motor Tests	Parameters Identified	Identification method
Back EMF Test	Number of Pole Pairs (p) Flux Linkage Constant (λ) Torque Constant (K_t)	Calculation
Friction Test	Viscous Damping Coefficient (b) Coulomb Friction (J_0)	Curve fitting
Coast Down Test	Rotor Inertia (J)	Curve fitting
DC Voltage Step Test	Resistance (R) Inductance (L)	Parameter estimation

https://www.mathworks.com/company/newsletters/articles/creating-a-high-fidelity-model-of-an-electric-motor-for-control-system-design-and-verification.html

Saturation Model



$$\lambda_d[n] = \lambda_d[n-1] + T_S\left(v_d[n] - R_S i_d[n-1] + \omega_e[n-1]\lambda_q[n-1]\right)$$

$$\lambda_q[n] = \lambda_q[n-1] + T_S\left(v_q[n] - R_S i_q[n-1] - \omega_e[n-1]\lambda_d[n-1]\right)$$

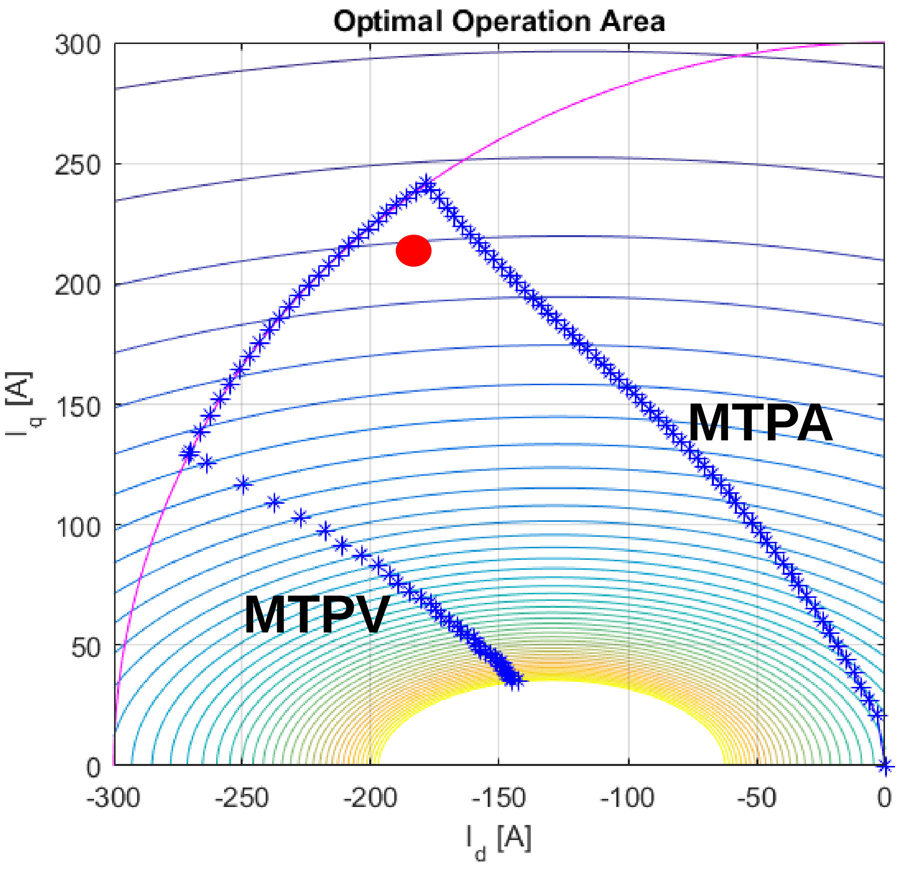
$$T_e[n] = \frac{3}{2}\frac{p}{2}\left(\lambda_d[n] i_q[n] - \lambda_q[n] i_d[n]\right)$$

$$\omega_{rm}[n] = \omega_{rm}[n-1] + T_S(1/J)(T_e[n] - T_L[n] - B\omega_{rm}[n-1])$$

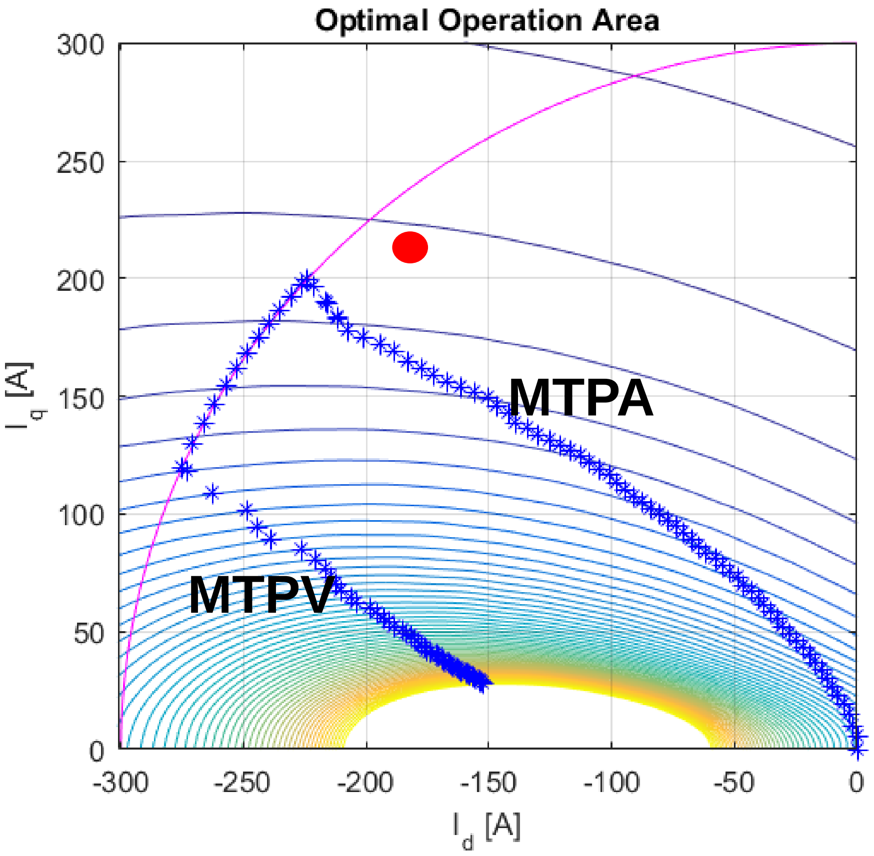
$$\omega_e[n] = PP \cdot \omega_{rm}[n]$$

Impact of Saturation on Flux-Weakening Operation

- The optimal FW operation area is the enclosed area defined by the MTPA and MTPV line

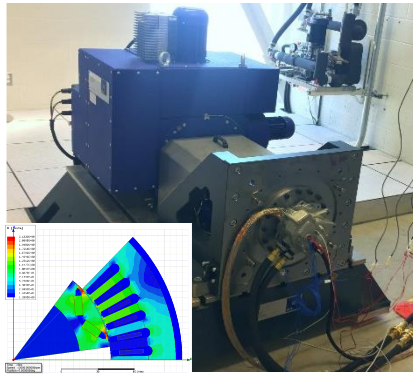


Linear Model

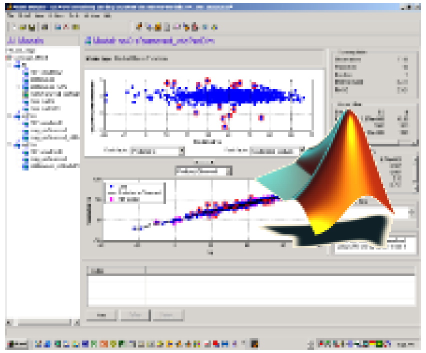


Saturation Model

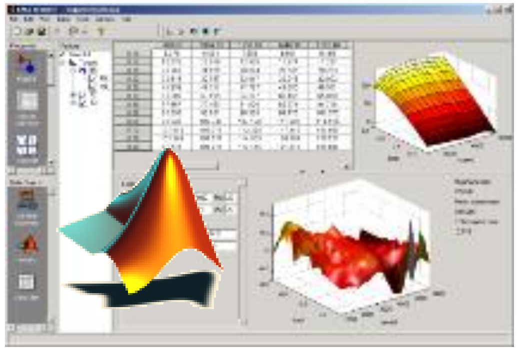
Bonus: Generating optimal torque control and flux-weakening calibration using Model-Based Calibration Toolbox (MBC)



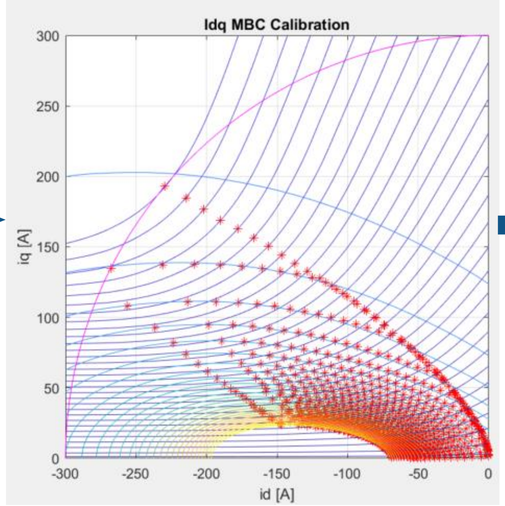
DoE

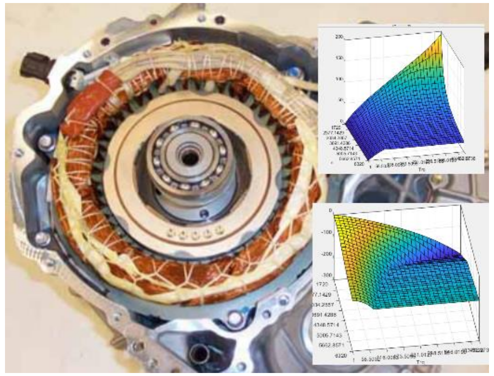


Data Modeling



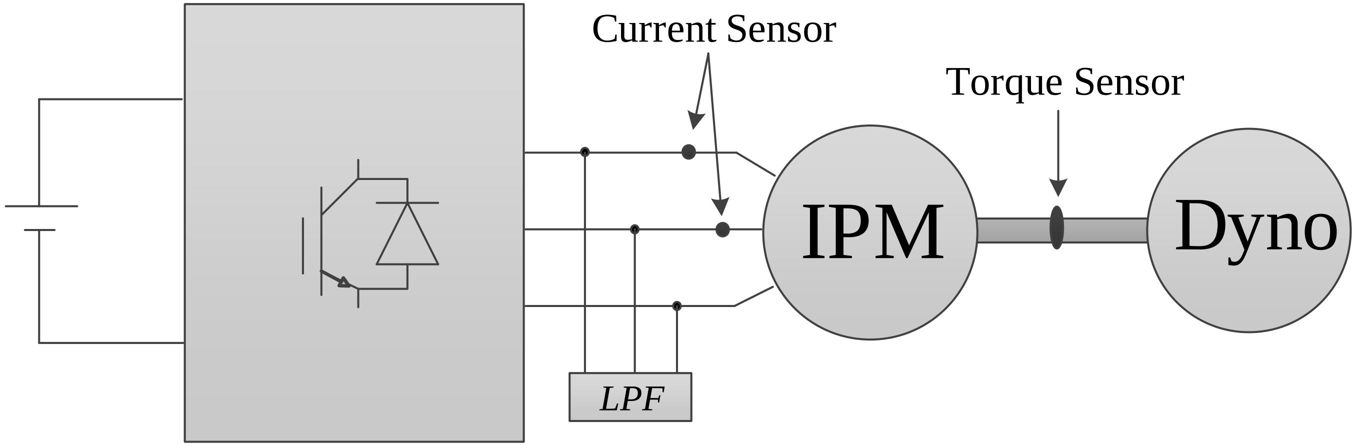
Calibration



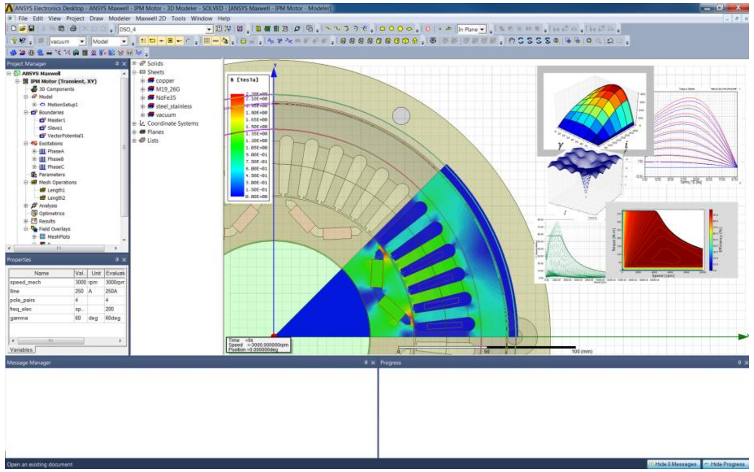


Implementation

Two Ways to Obtain Saturation Data

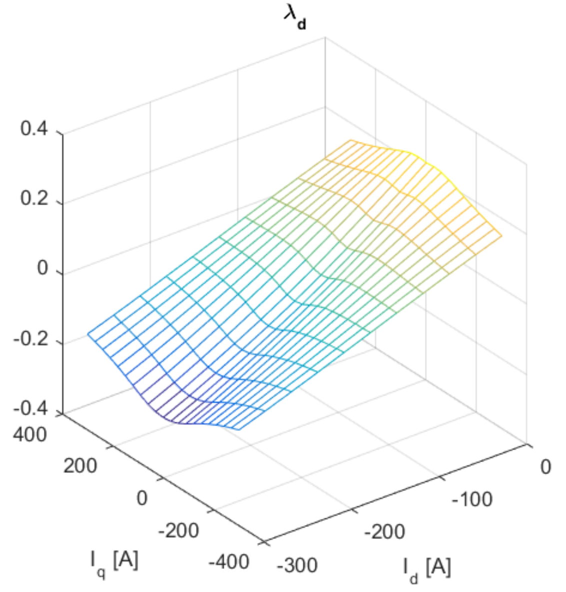


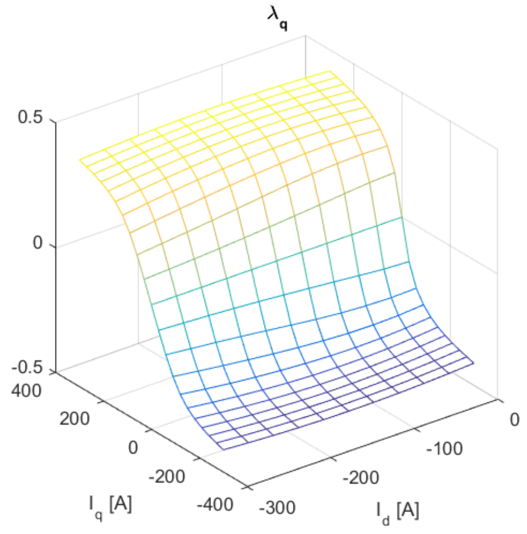
Dyno testing

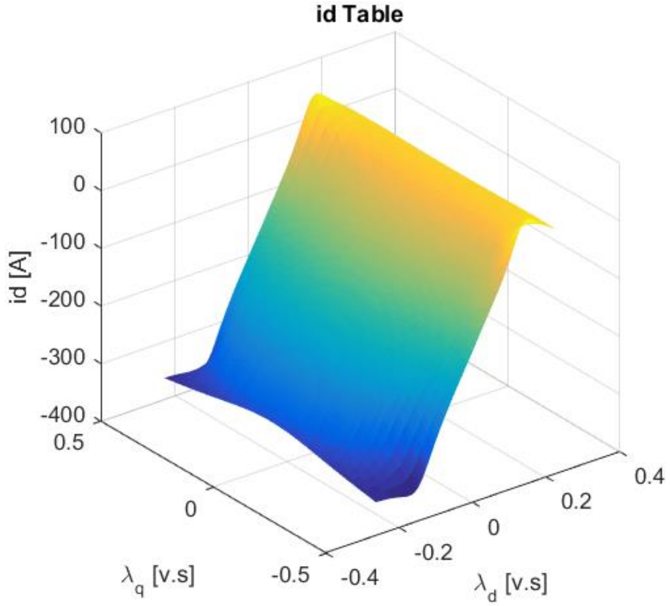


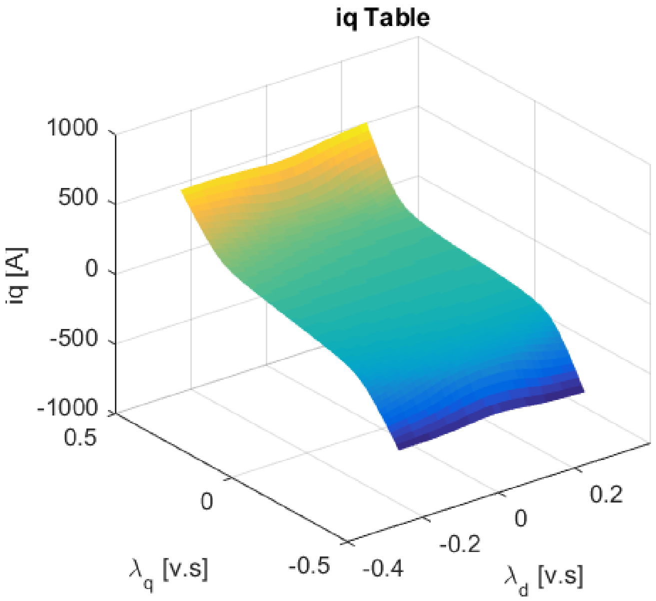
FEA

Nonlinear Flux and Current Tables

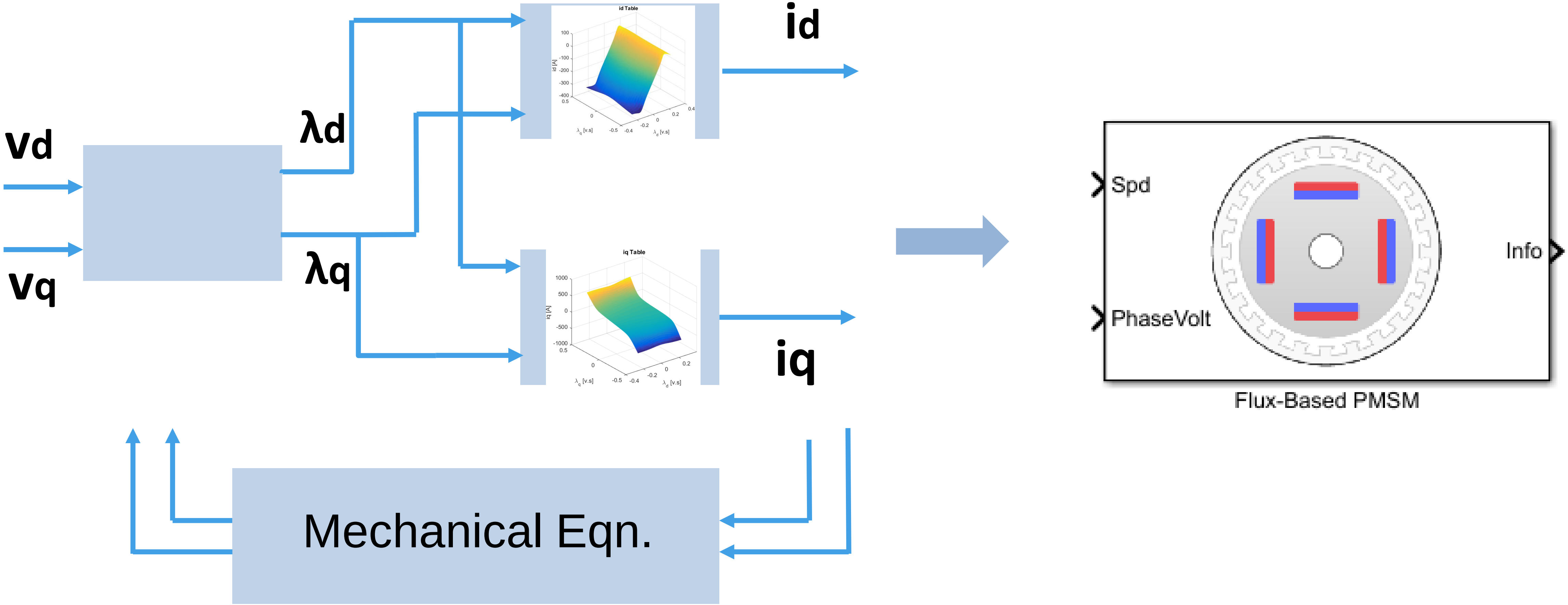




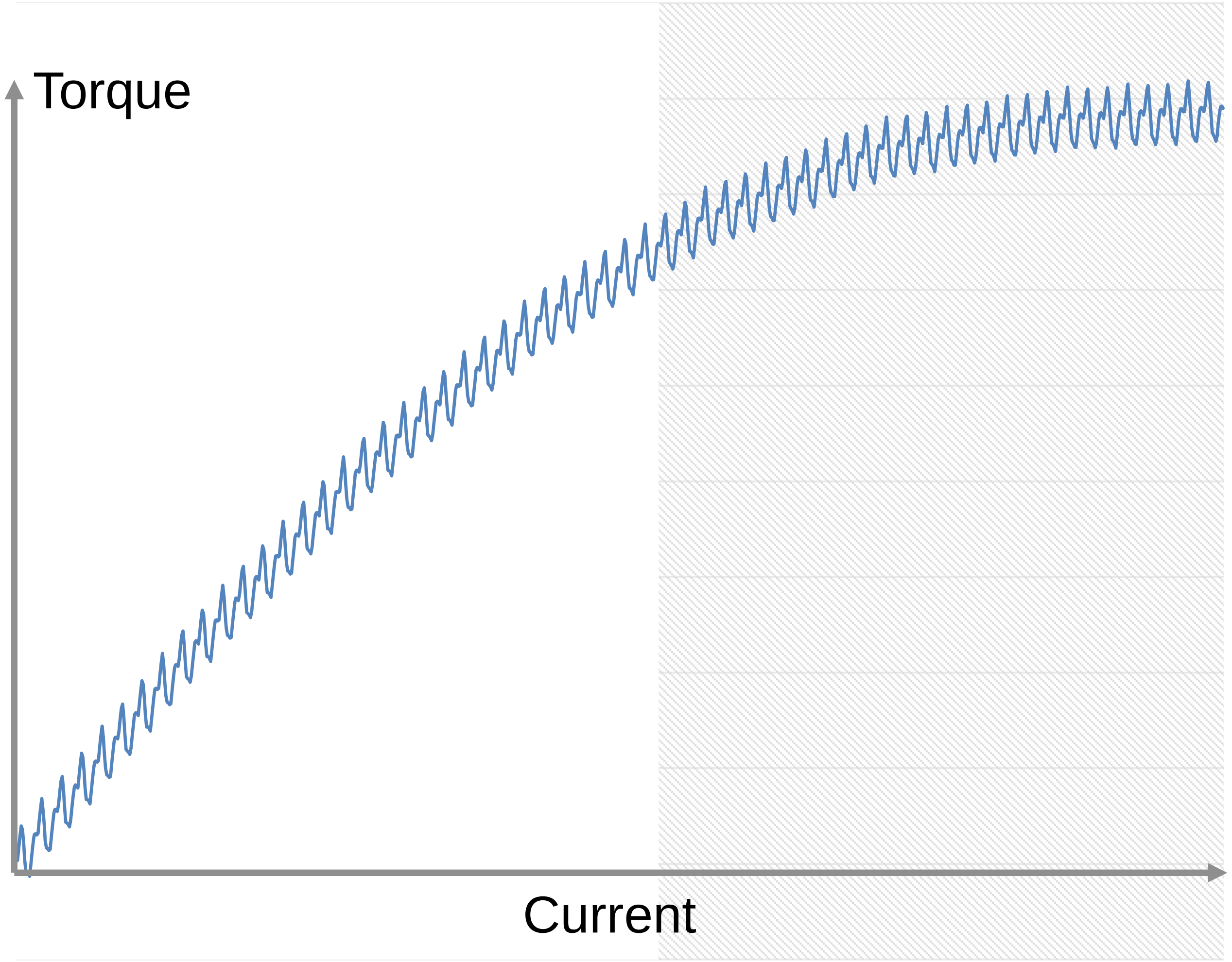




Saturation PMSM Model in Powertrain Blockset



Saturation + Spatial Harmonics Model



> If you compare a 2004 and a 2014 Toyota Prius, you will see that the amount of suspension used for vibration-mitigation has been greatly reduced.

THE TECH

A CLOSER LOOK AT TORQUE RIPPLE

Q&A with Dr. Nir Vaks,
Co-founder and CTO at Continuous Solutions
By Christian Ruoff

Traction Motor

Minimization of torque ripple is important for motors in many applications, because it is one of the main causes of vibration.

Switched Reluctance Motor

Figure 1: A typical SRM "6/4" design

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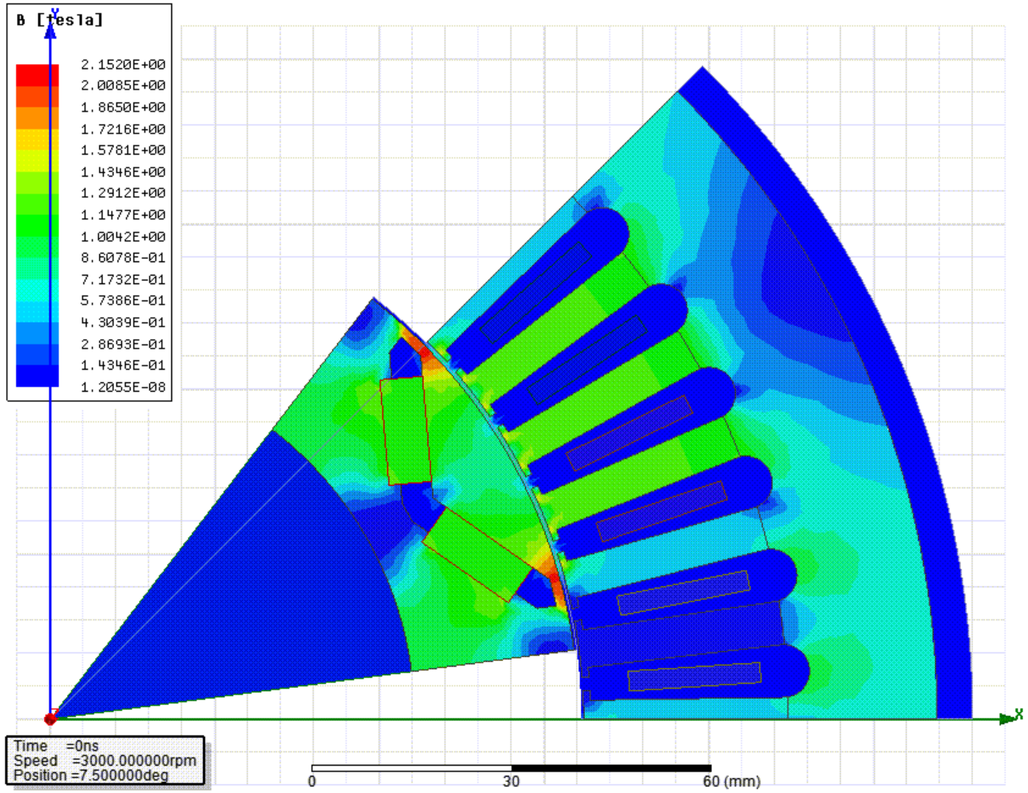
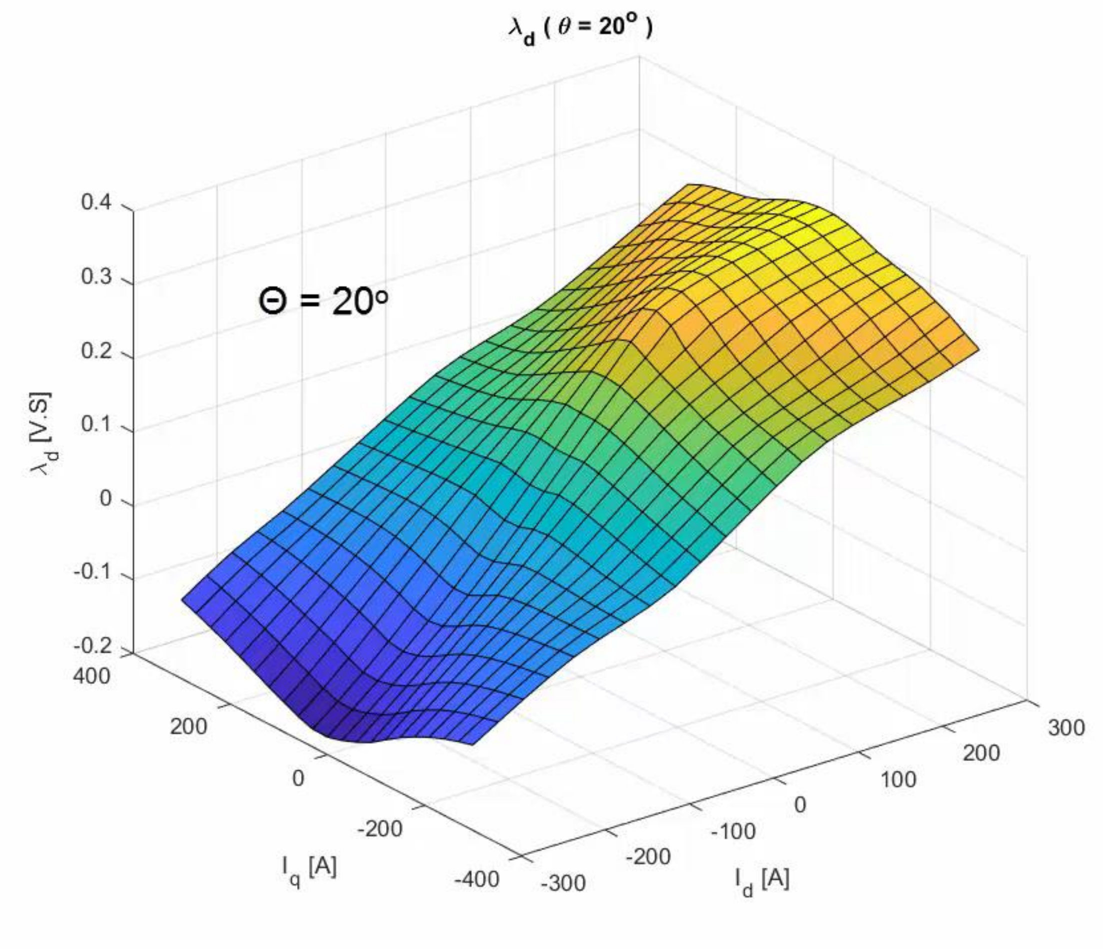
JUL/AUG 2015 23

Reference: https://chargedevs.com/features/minimization-of-torque-ripple-is-important-for-motors-in-many-applications-because-it-is-one-of-the-main-causes-of-vibration/

Rotor Position Dependency



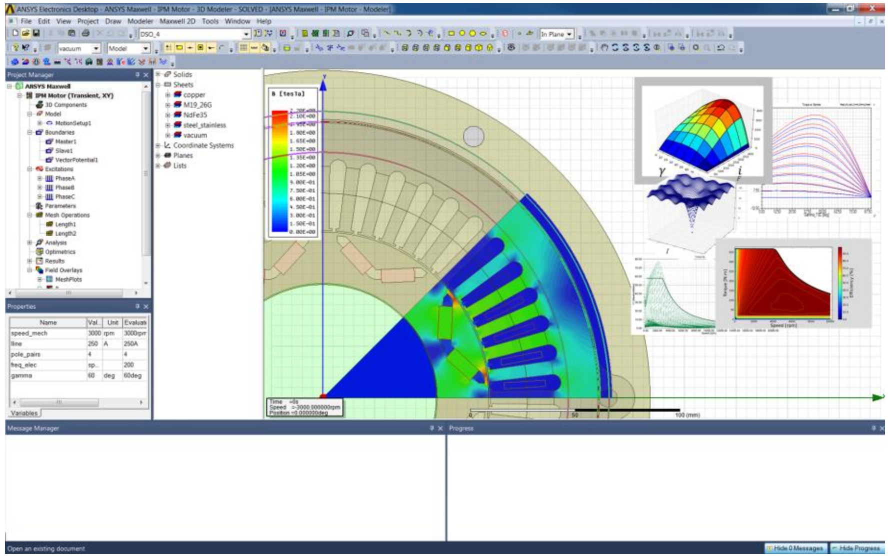


Animation: flux variation at different rotor position

How to Obtain Saturation + Spatial Harmonics Data ?

Current

Rotor Position



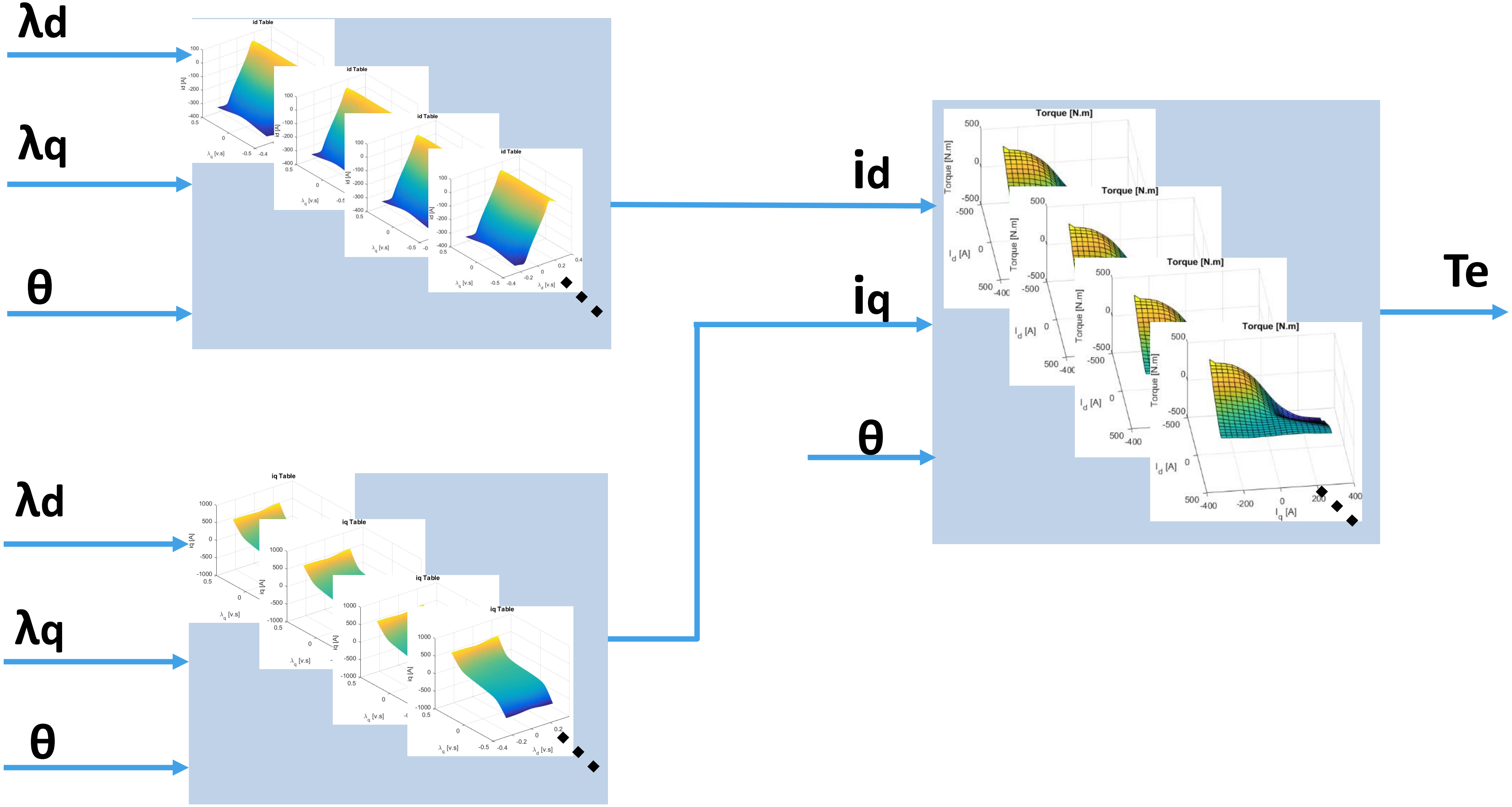
Name	Val...	Unit	Evaluat
speed_mech	3000	rpm	3000rpm
Iline	250	A	250A
pole_pairs	4		4
freq_elec	sp...		200
gamma	60	deg	60deg

Flux Linkage

Torque

Sweep in FEA Tool

Saturation + Spatial Harmonics Model Core Structure in Simulink



λd

λq

θ

id

iq

θ

Te

λd

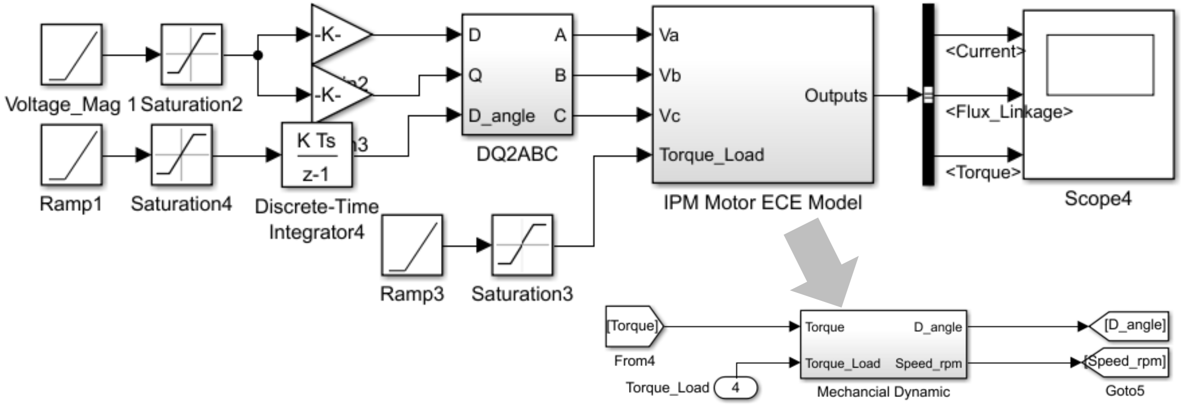
λq

θ

Saturation + Spatial Harmonics Model Validation Using ANSYS Maxwell FEA Data

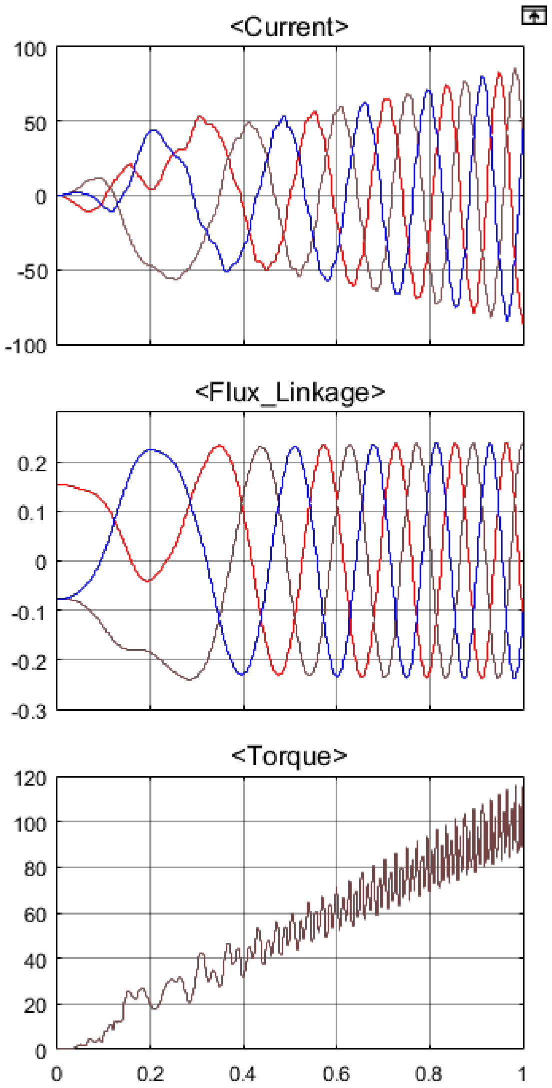
Voltage input with mechanical dynamic Mechanical & Electrical

Flux to Current Lookup - Inversed Maxwell Result
Mechanical Transient Display
Voltage = 50, Frequency = 20 Hz (300rpm Steady State),
Load Torque = 250Nm, Rotor Inertia = 0.054
Phase Resistance = 0.069 Ohm

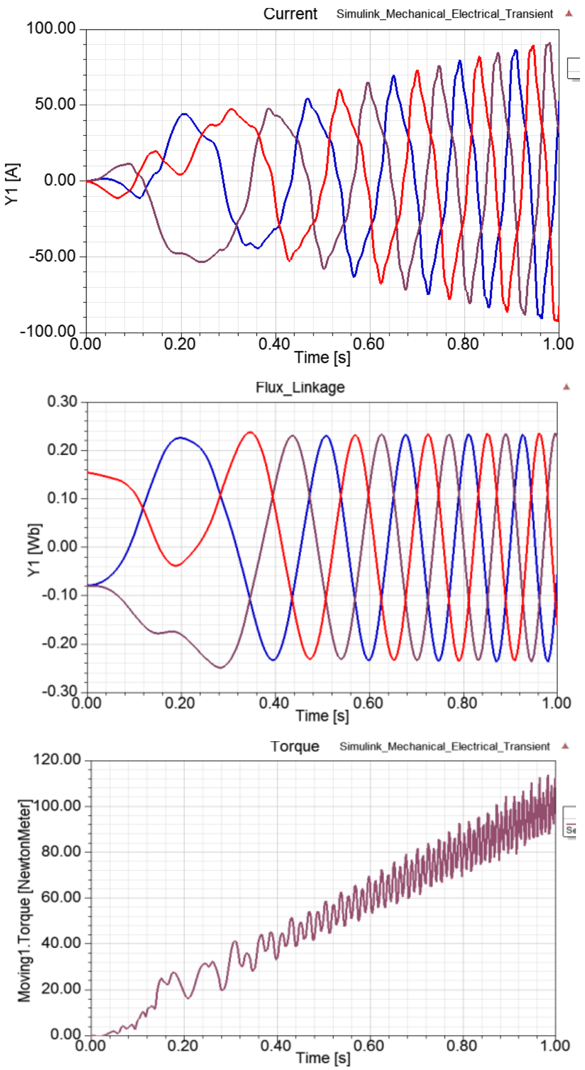


- Simulink result is compared with Maxwell result. The results are very close.
- Mechanical dynamic is considered.

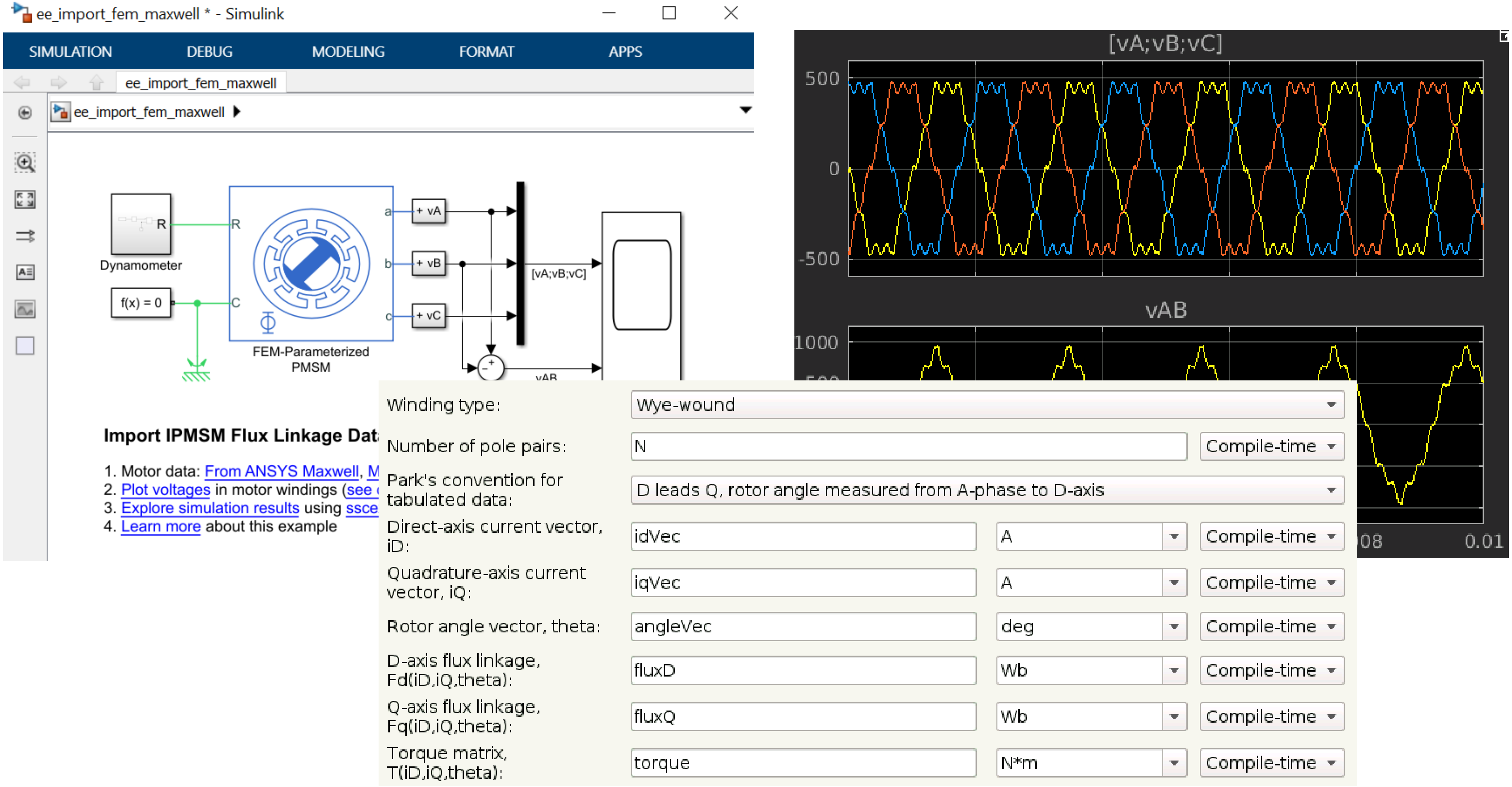
Simulink Result



Maxwell Result



Example: Importing PMSM data from ANSYS Maxwell (since R2018a)



Import IPMSM Flux Linkage Dat

1. Motor data: From ANSYS Maxwell, M
2. Plot voltages in motor windings (see
3. Explore simulation results using ssce
4. Learn more about this example

Winding type:	Wye-wound		
Number of pole pairs:	N		Compile-time
Park's convention for tabulated data:	D leads Q, rotor angle measured from A-phase to D-axis		
Direct-axis current vector, iD:	idVec	A	Compile-time
Quadrature-axis current vector, iQ:	iqVec	A	Compile-time
Rotor angle vector, theta:	angleVec	deg	Compile-time
D-axis flux linkage, Fd(iD,iQ,theta):	fluxD	Wb	Compile-time
Q-axis flux linkage, Fq(iD,iQ,theta):	fluxQ	Wb	Compile-time
Torque matrix, T(iD,iQ,theta):	torque	N*m	Compile-time

Example: Importing PMSM data from ANSYS Maxwell (R2018a)

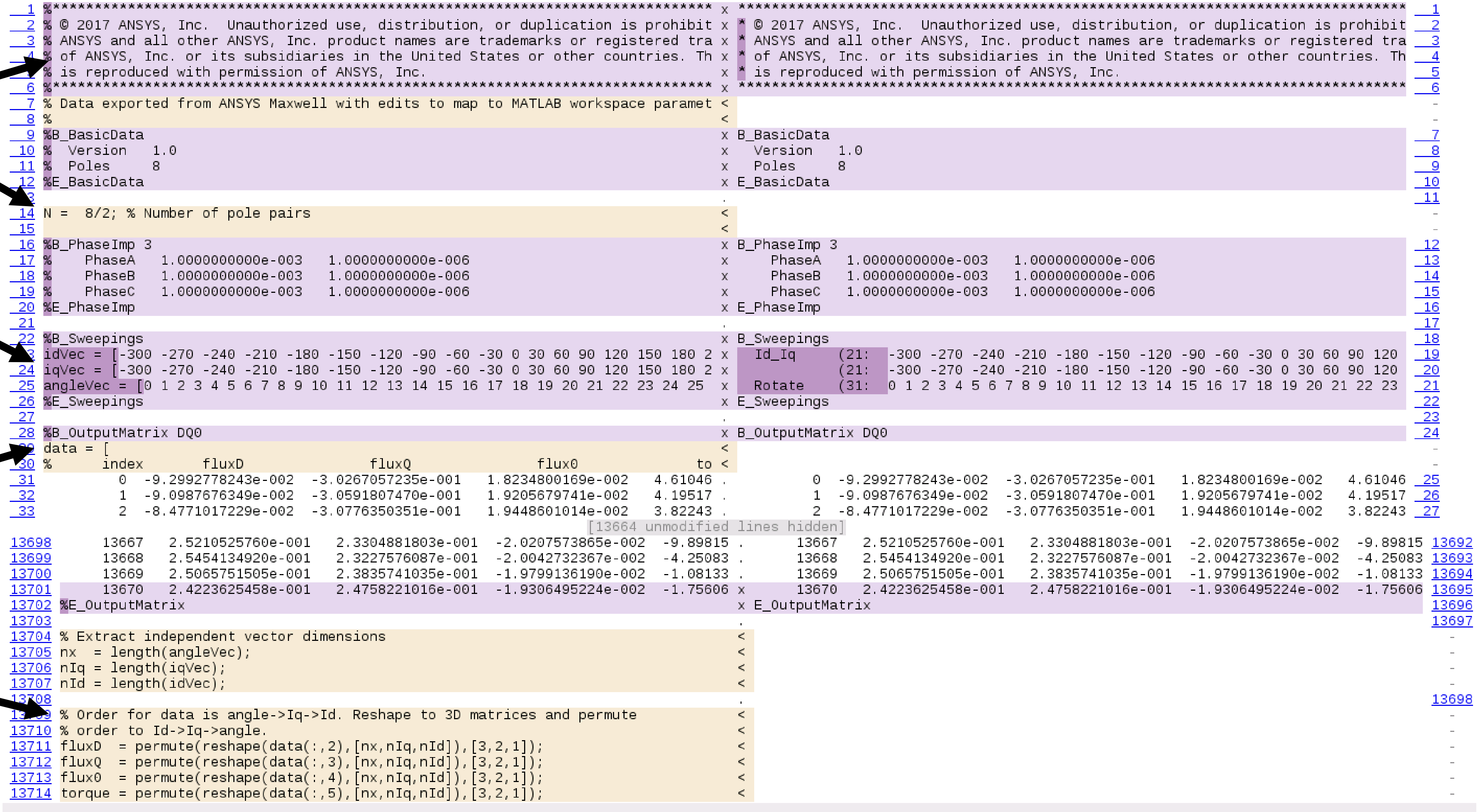
1. Swap comment character *->%

2. Define # pole pairs

3. Fix syntax defining independent vectors

4. Put data into MATLAB array

5. Reshape into MATLAB 3D arrays and re-order independent variables



```
%******************************************************************************* x ********************************************************************************
% © 2017 ANSYS, Inc.  Unauthorized use, distribution, or duplication is prohibit x * © 2017 ANSYS, Inc.  Unauthorized use, distribution, or duplication is prohibit
% ANSYS and all other ANSYS, Inc. product names are trademarks or registered tra x * ANSYS and all other ANSYS, Inc. product names are trademarks or registered tra
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% is reproduced with permission of ANSYS, Inc.                                   x * is reproduced with permission of ANSYS, Inc.
%******************************************************************************* x ********************************************************************************
% Data exported from ANSYS Maxwell with edits to map to MATLAB workspace paramet <
%                                                                                <
%B_BasicData                                                                     x B_BasicData
%  Version   1.0                                                                 x   Version   1.0
%  Poles     8                                                                   x   Poles     8
%E_BasicData                                                                     x E_BasicData
                                                                                 .
N =  8/2; % Number of pole pairs                                                 <
                                                                                 <
%B_PhaseImp 3                                                                    x B_PhaseImp 3
%    PhaseA   1.0000000000e-003   1.0000000000e-006                              x     PhaseA   1.0000000000e-003   1.0000000000e-006
%    PhaseB   1.0000000000e-003   1.0000000000e-006                              x     PhaseB   1.0000000000e-003   1.0000000000e-006
%    PhaseC   1.0000000000e-003   1.0000000000e-006                              x     PhaseC   1.0000000000e-003   1.0000000000e-006
%E_PhaseImp                                                                      x E_PhaseImp
                                                                                 .
%B_Sweepings                                                                     x B_Sweepings
idVec = [-300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 2 x   Id_Iq      (21: -300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120
iqVec = [-300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 2 x              (21: -300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120
angleVec = [0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25  x   Rotate     (31: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
%E_Sweepings                                                                     x E_Sweepings
                                                                                 .
%B_OutputMatrix DQ0                                                              x B_OutputMatrix DQ0
data = [                                                                         <
%      index        fluxD                fluxQ                flux0           to <
           0  -9.2992778243e-002  -3.0267057235e-001   1.8234800169e-002   4.61046 .        0  -9.2992778243e-002  -3.0267057235e-001   1.8234800169e-002   4.61046
           1  -9.0987676349e-002  -3.0591807470e-001   1.9205679741e-002   4.19517 .        1  -9.0987676349e-002  -3.0591807470e-001   1.9205679741e-002   4.19517
           2  -8.4771017229e-002  -3.0776350351e-001   1.9448601014e-002   3.82243 .        2  -8.4771017229e-002  -3.0776350351e-001   1.9448601014e-002   3.82243
                                      [13664 unmodified lines hidden]
       13667   2.5210525760e-001   2.3304881803e-001  -2.0207573865e-002  -9.89815 .    13667   2.5210525760e-001   2.3304881803e-001  -2.0207573865e-002  -9.89815
       13668   2.5454134920e-001   2.3227576087e-001  -2.0042732367e-002  -4.25083 .    13668   2.5454134920e-001   2.3227576087e-001  -2.0042732367e-002  -4.25083
       13669   2.5065751505e-001   2.3835741035e-001  -1.9799136190e-002  -1.08133 .    13669   2.5065751505e-001   2.3835741035e-001  -1.9799136190e-002  -1.08133
       13670   2.4223625458e-001   2.4758221016e-001  -1.9306495224e-002  -1.75606 x    13670   2.4223625458e-001   2.4758221016e-001  -1.9306495224e-002  -1.75606
%E_OutputMatrix                                                                     x E_OutputMatrix
                                                                                    .
% Extract independent vector dimensions                                             <
nx  = length(angleVec);                                                             <
nIq = length(iqVec);                                                                <
nId = length(idVec);                                                                <
                                                                                    .
% Order for data is angle->Iq->Id. Reshape to 3D matrices and permute               <
% order to Id->Iq->angle.                                                           <
fluxD  = permute(reshape(data(:,2),[nx,nIq,nId]),[3,2,1]);                          <
fluxQ  = permute(reshape(data(:,3),[nx,nIq,nId]),[3,2,1]);                          <
flux0  = permute(reshape(data(:,4),[nx,nIq,nId]),[3,2,1]);                          <
torque = permute(reshape(data(:,5),[nx,nIq,nId]),[3,2,1]);                          <
```

Takeaways

- It is up to motor control engineers to choose the proper level of model fidelity for different applications.
- High fidelity motor model facilitates the development of motor control algorithms.
- Whether you have dyno testing data or FEA data, Simulink and Simscape can be the platform for high fidelity motor modeling.