Deriving a Fast and Accurate PMSM Motor Model from Finite Element Analysis

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Haiwei Cai, Ph.D ANSYS Application Engineer

Motivation

- Traditionally, workflow of the machine design team and the control team have proceeded separately.
- DoE on a dyno setup requires an understanding of the machine characteristics and simulation can help determine a minimum number of points to test.
- Accurate torque ripple profile of a high fidelity machine model facilitates the development of torque ripple mitigation algorithms.

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- How to Obtain Saturation + Spatial Harmonics Data
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- Introduction of Maxwell Equivalent Circuit Extraction (ECE) Model
- Importing Raw Data from Maxwell Finite Element Result to Simulink
- Comparison between PMSM model in Simulink and Maxwell (FEA)

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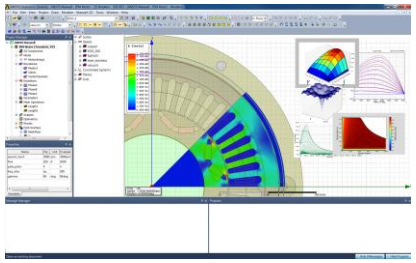
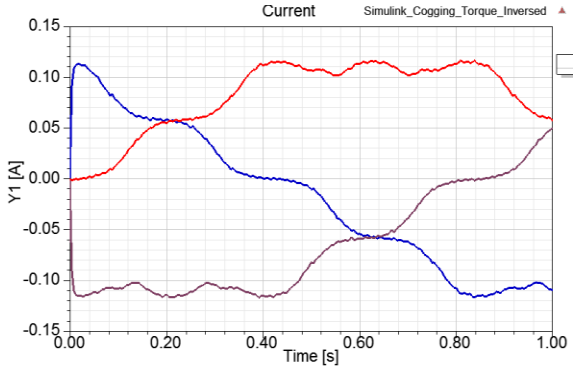
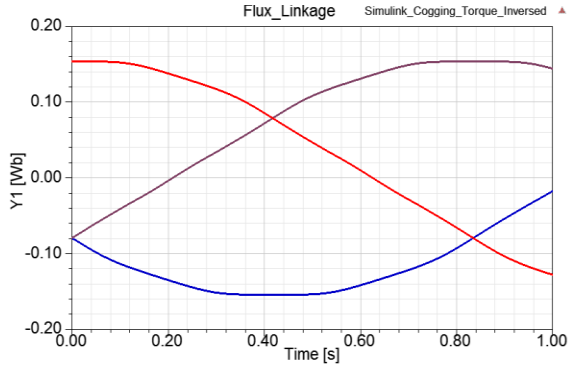
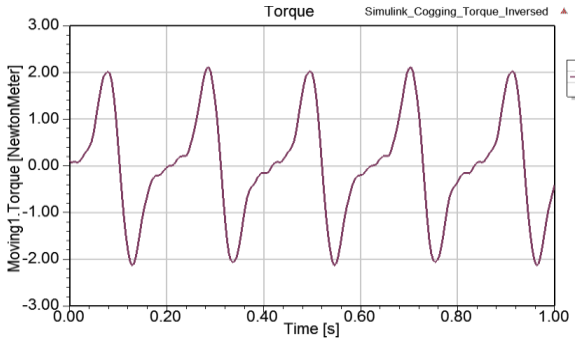
Objective and Workflow Overview

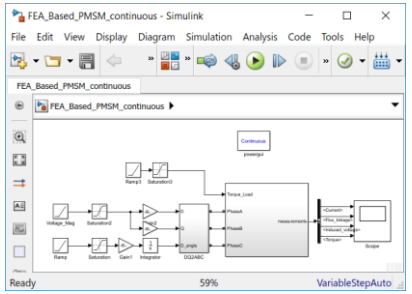


ANSYS Maxwell

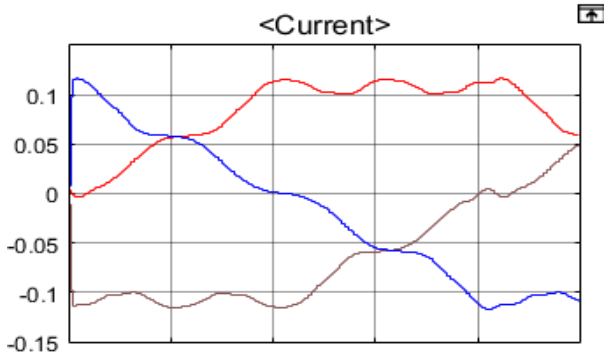


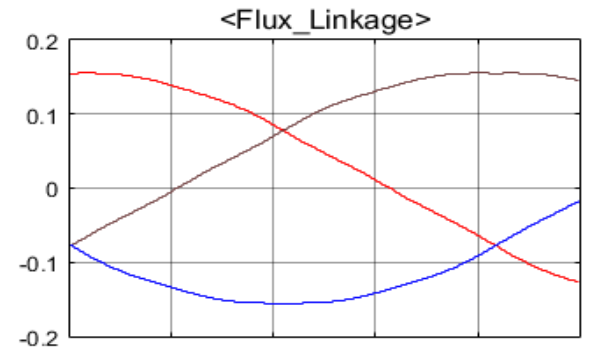


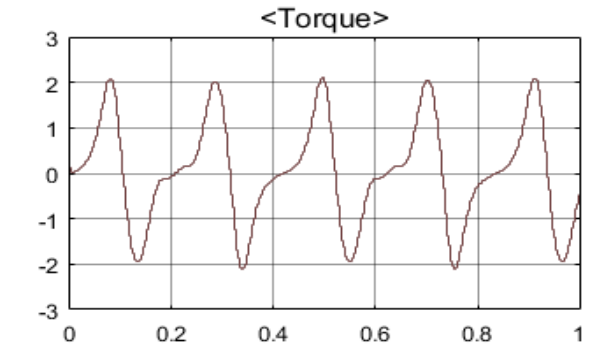




Simulink







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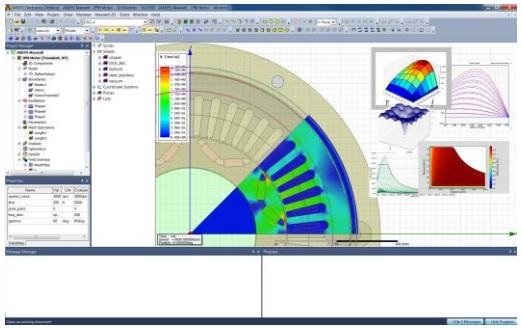

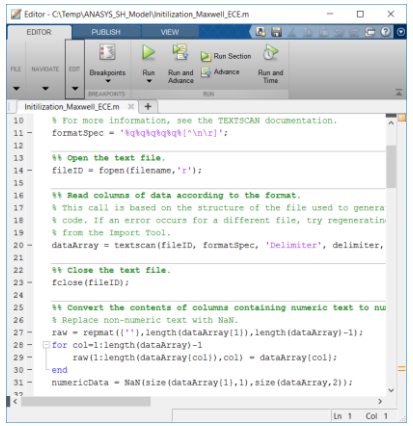

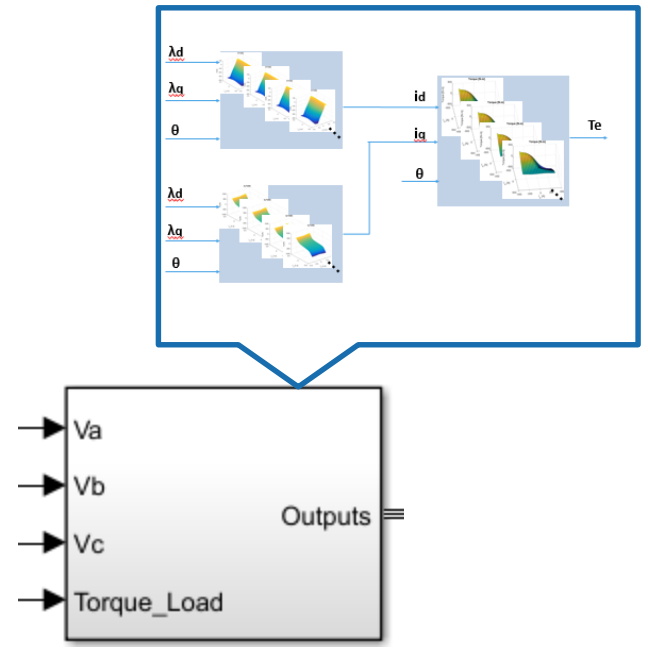

ANSYS Maxwell generates Model_RawData.txt file

Process raw data into proper format through MATLAB scripting

Bring processed data into Simulink saturation + harmonics motor model structure

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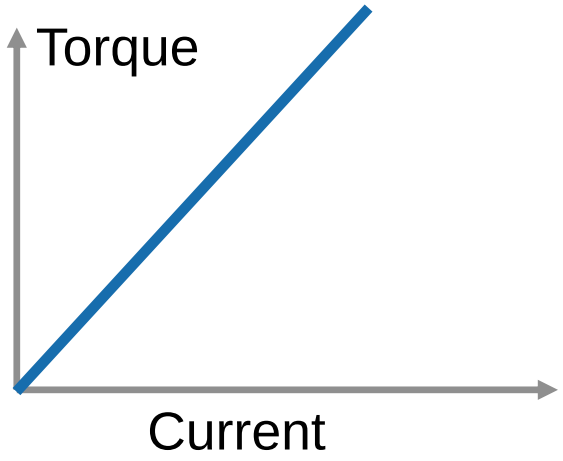
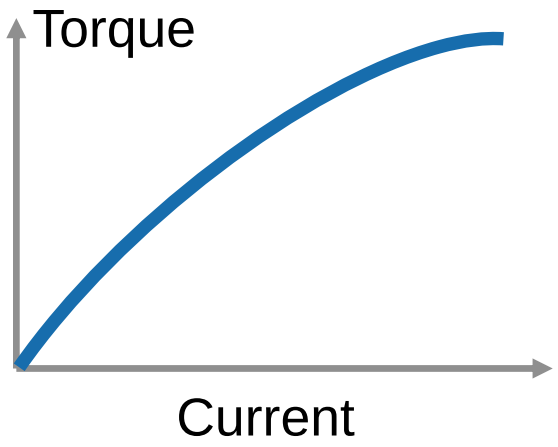
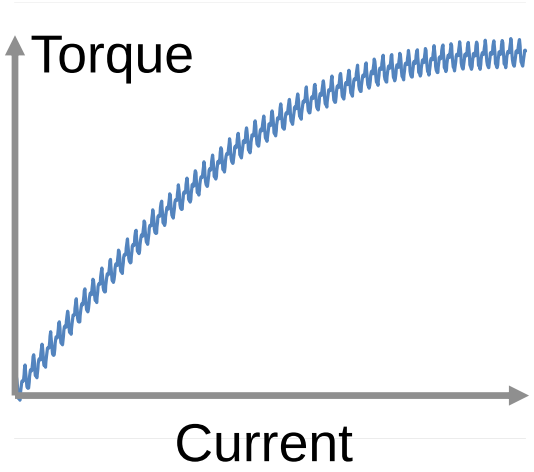
Three Levels of PMSM Model Fidelity



Lumped Parameter

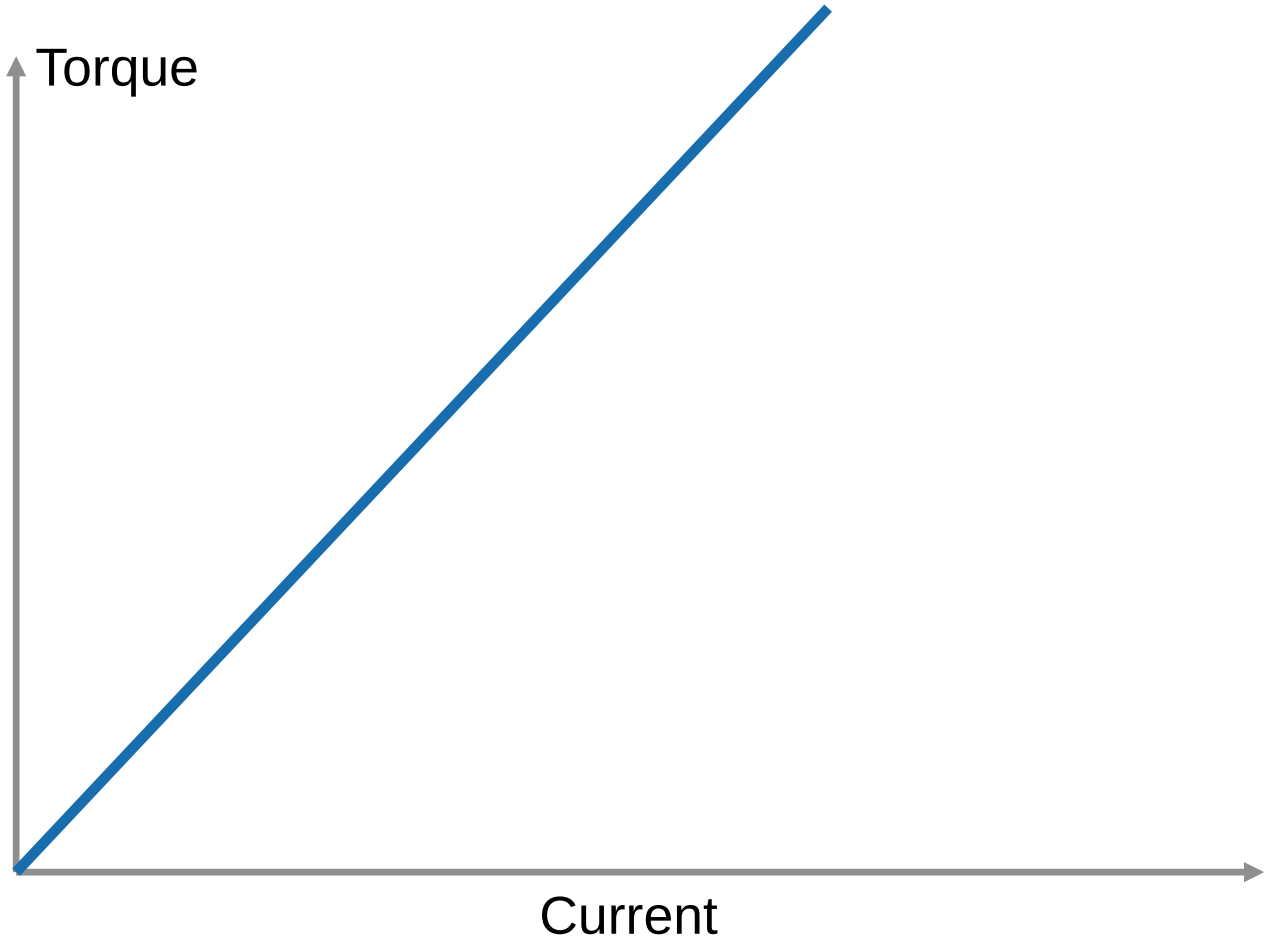


Saturation



Saturation +
Spatial Harmonics

Lumped-Parameter Model



Required Parameters

Electrical Model

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

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

$$\omega_e = p\omega_r$$

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

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

Mechanical Model

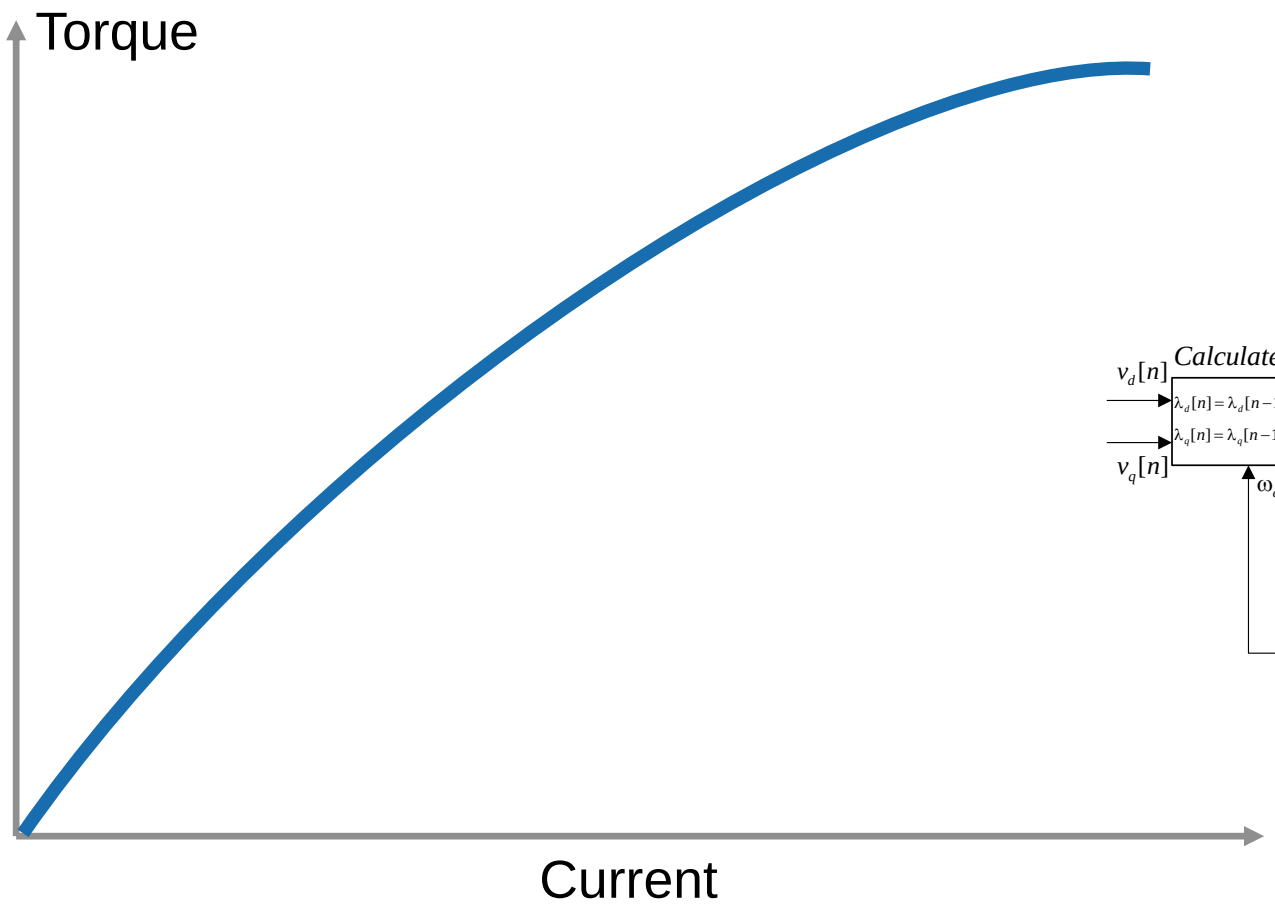
$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - sgn(\omega_r) J_0 - b\omega_r - T_{load})$$

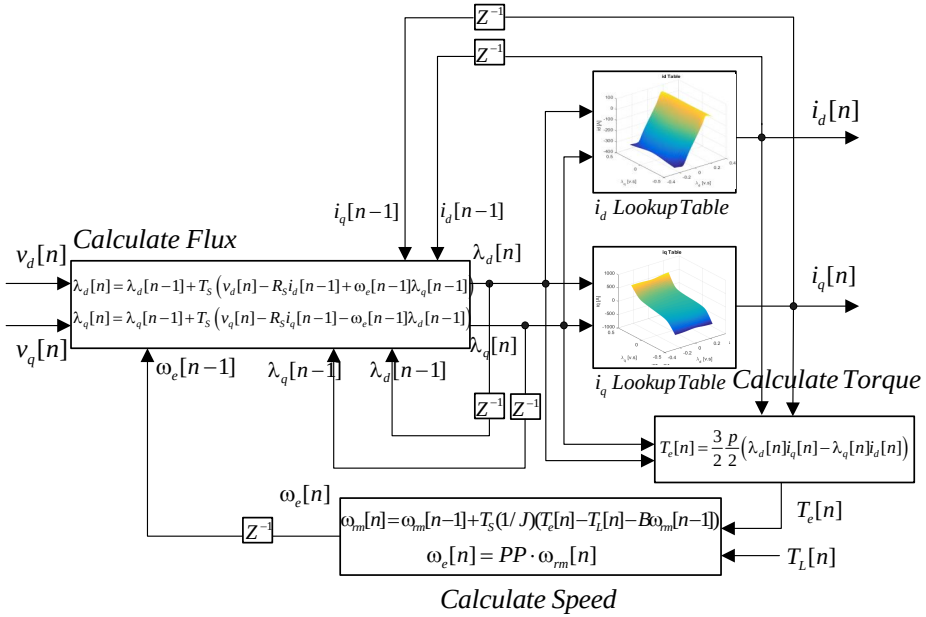
How to Get Those Parameters ?

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

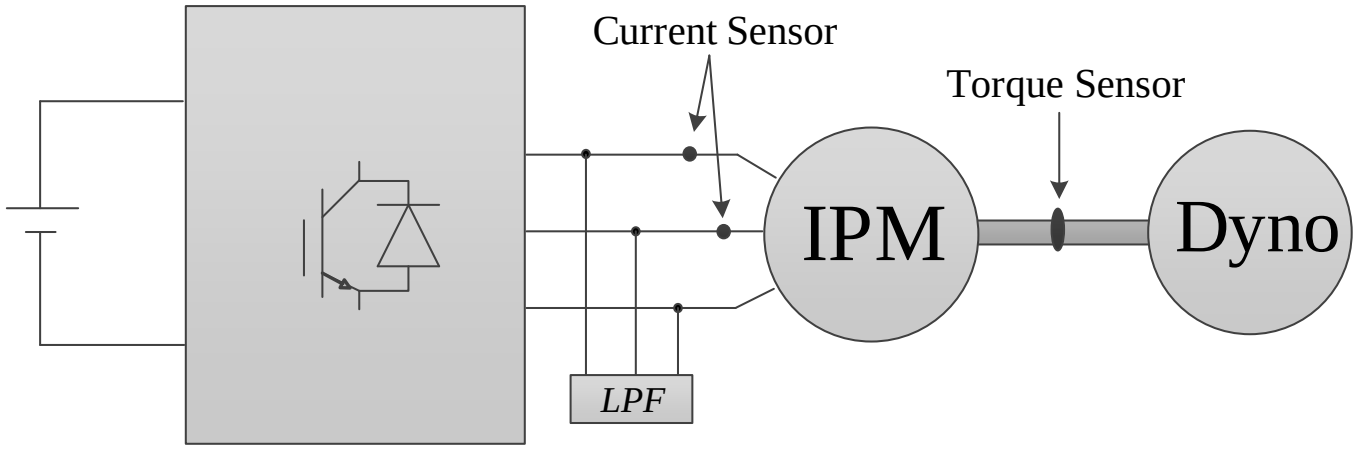
https://www.mathworks.com/company/newsletters/articles/creating-a-high-fidelity-model-of-an-electric-motor-for-control-system-design-and-verification.html

Saturation Model

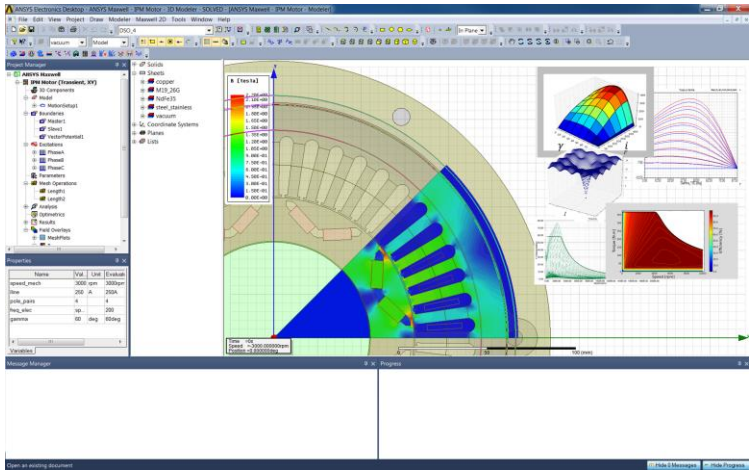




Two Ways to Obtain Saturation Data

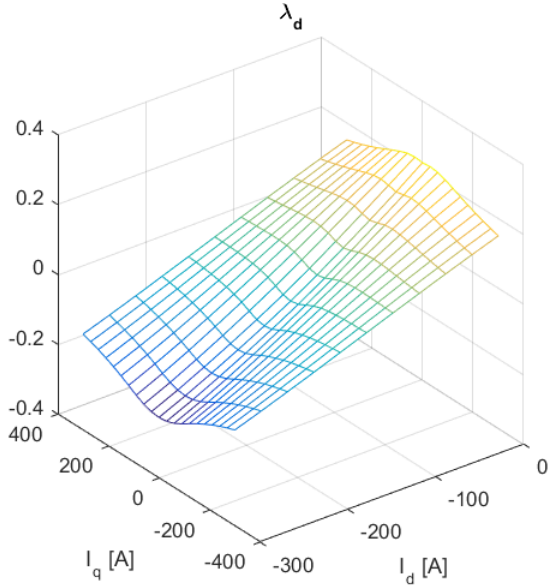


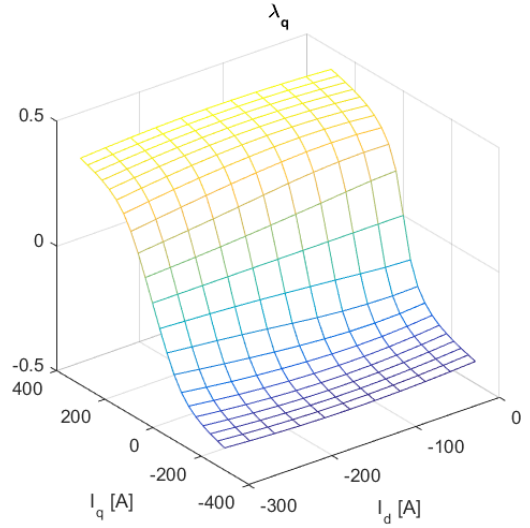
Dyno testing

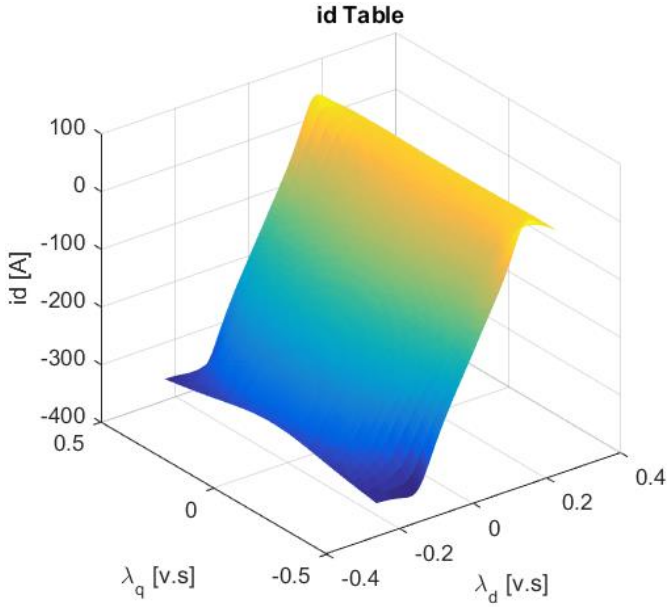


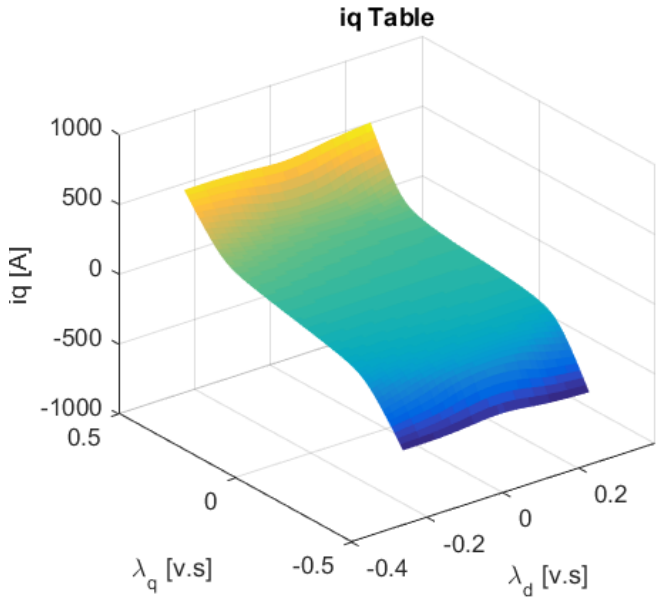
FEA

Nonlinear Flux and Current Tables

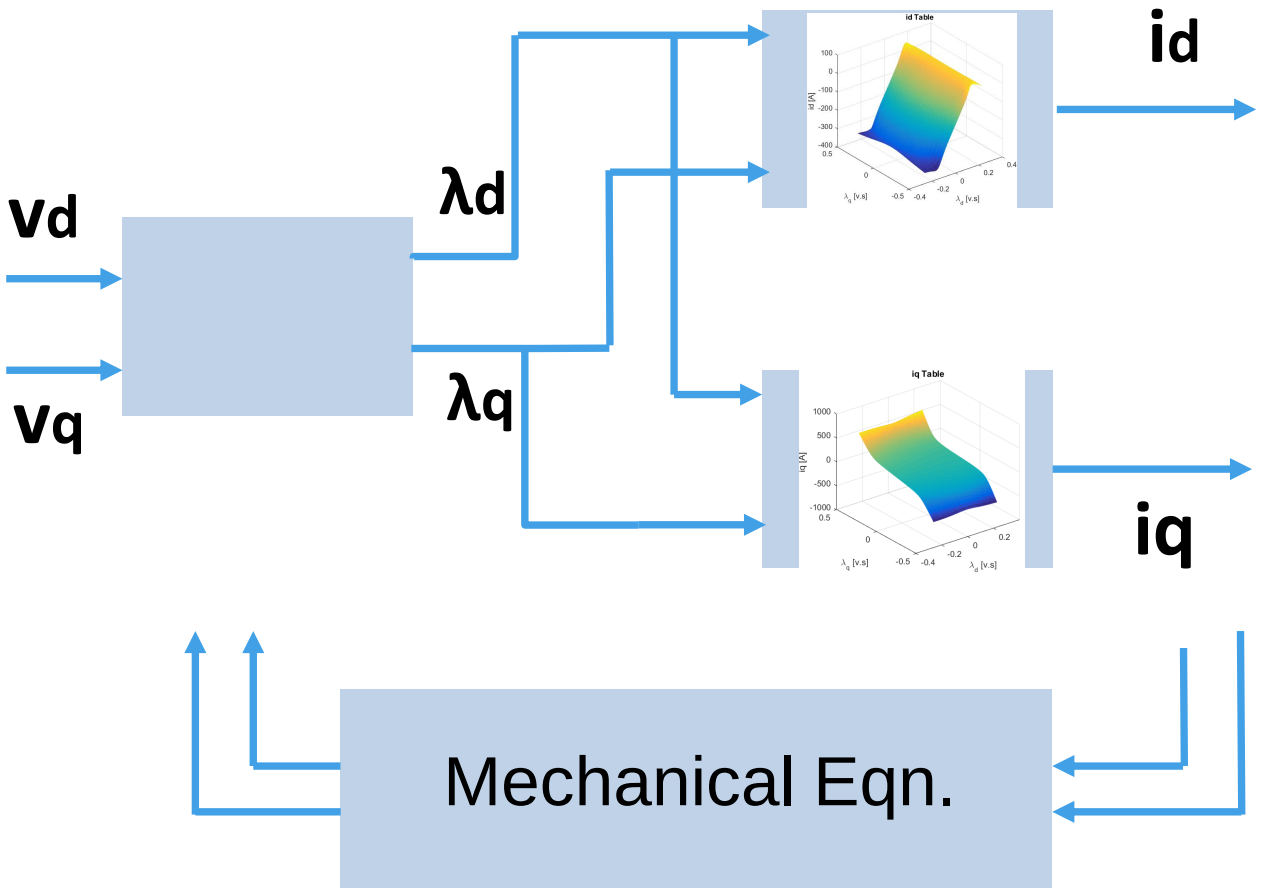


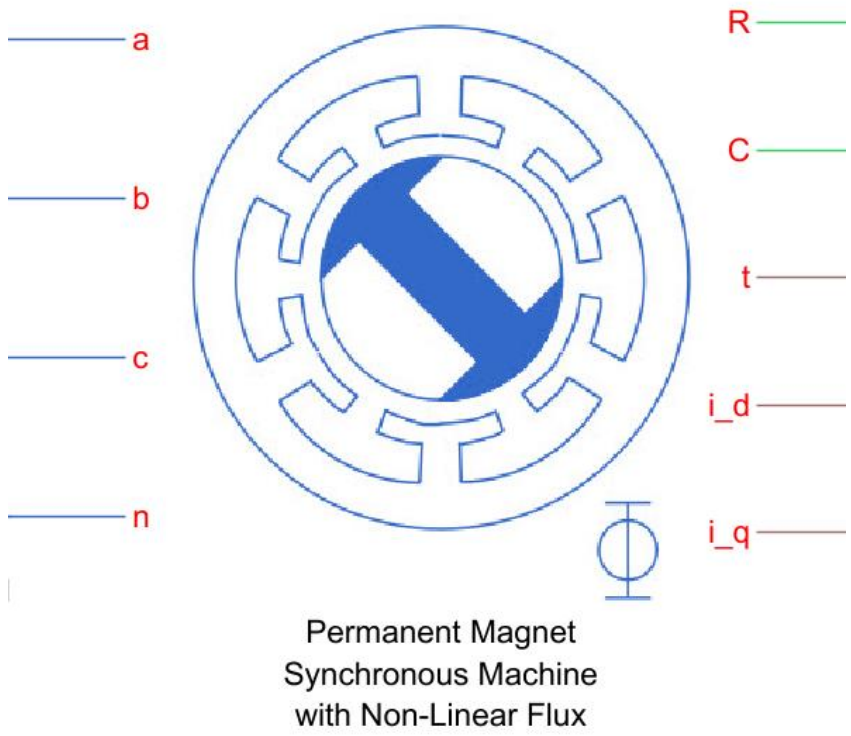




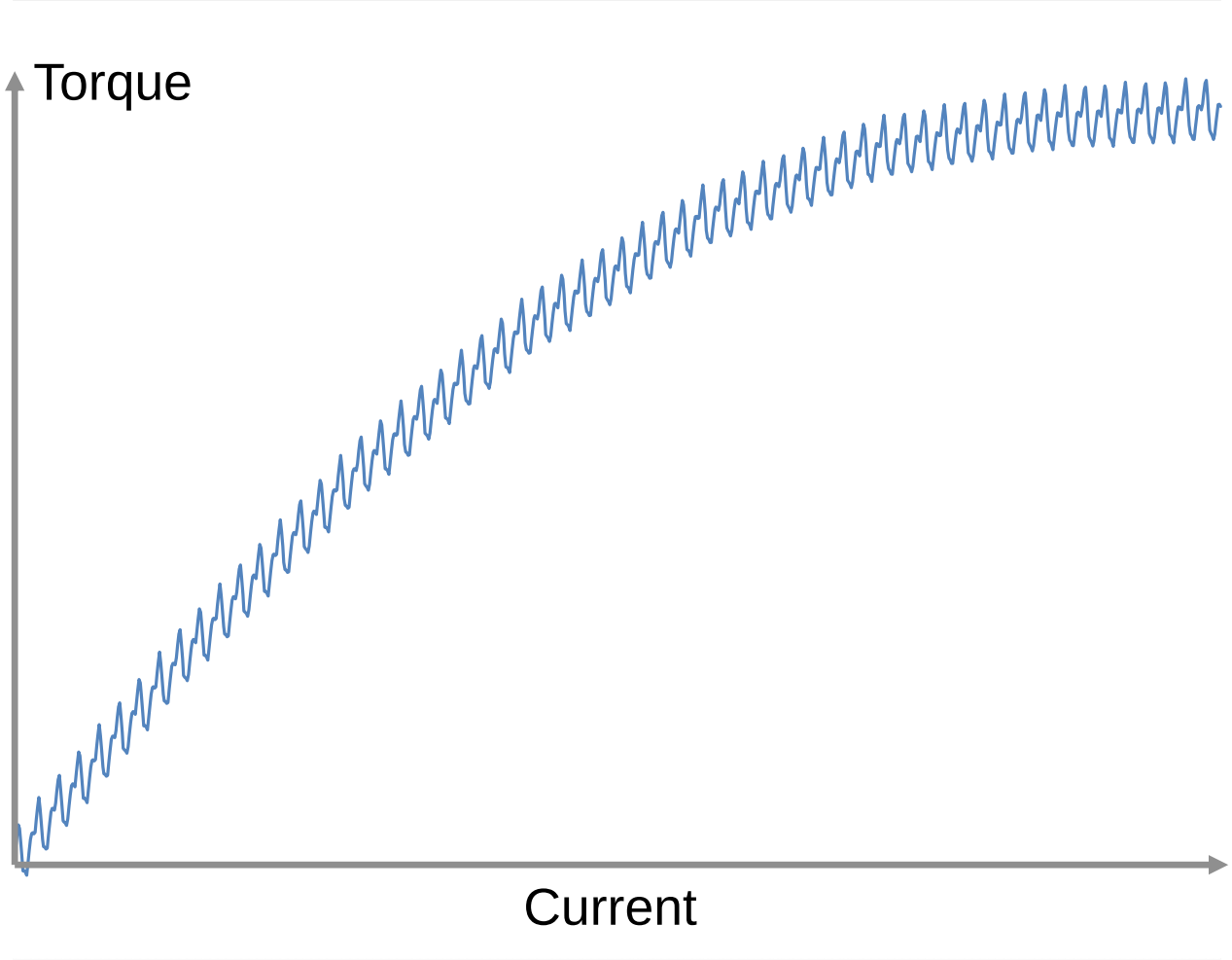


Saturation PMSM Model in Simscape

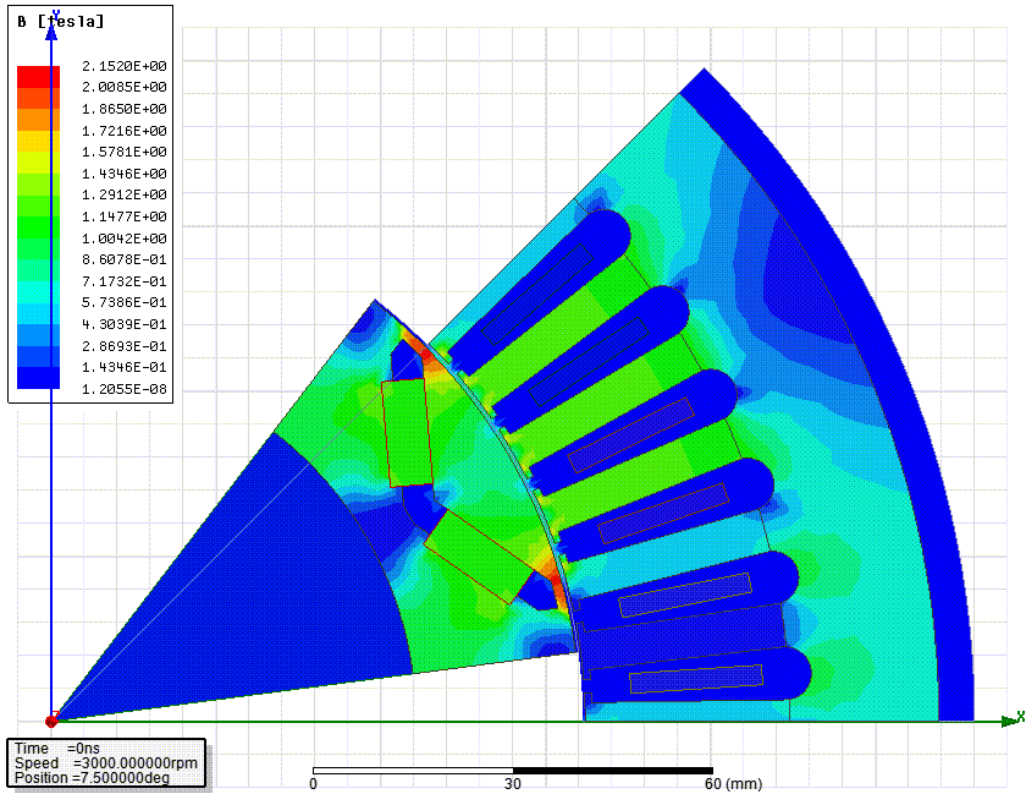


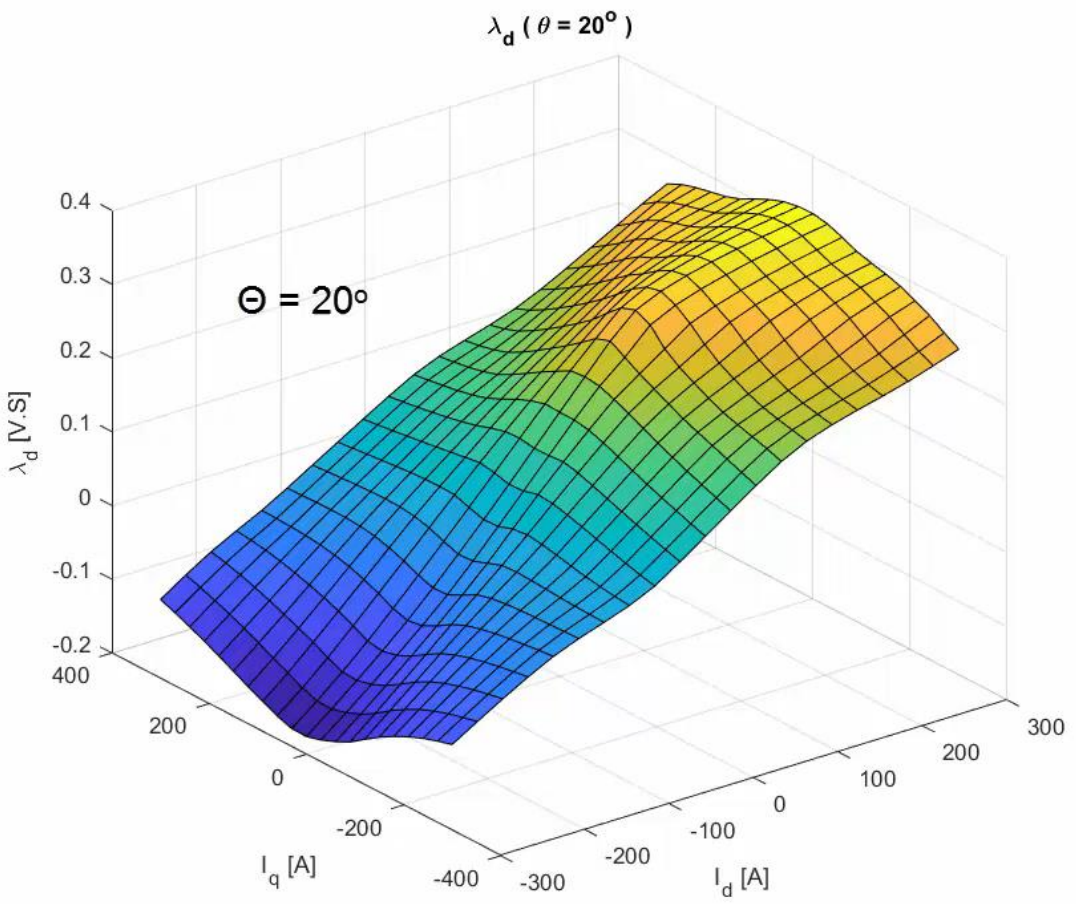


Saturation + Spatial Harmonics Model



Rotor Position Dependency





Animation: flux variation at different rotor position

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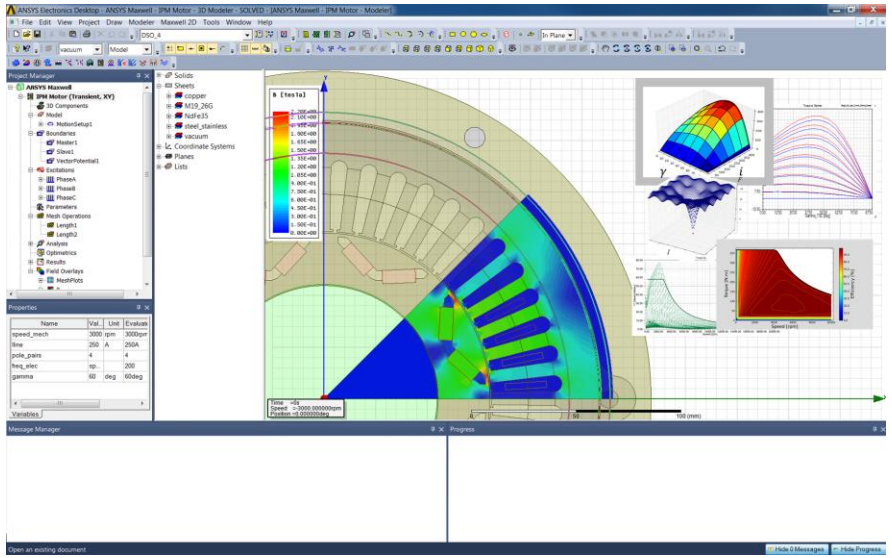
How to Obtain Saturation + Spatial Harmonics Data ?

Current

Rotor Position



Flux Linkage

Torque

Sweep in FEA Tool

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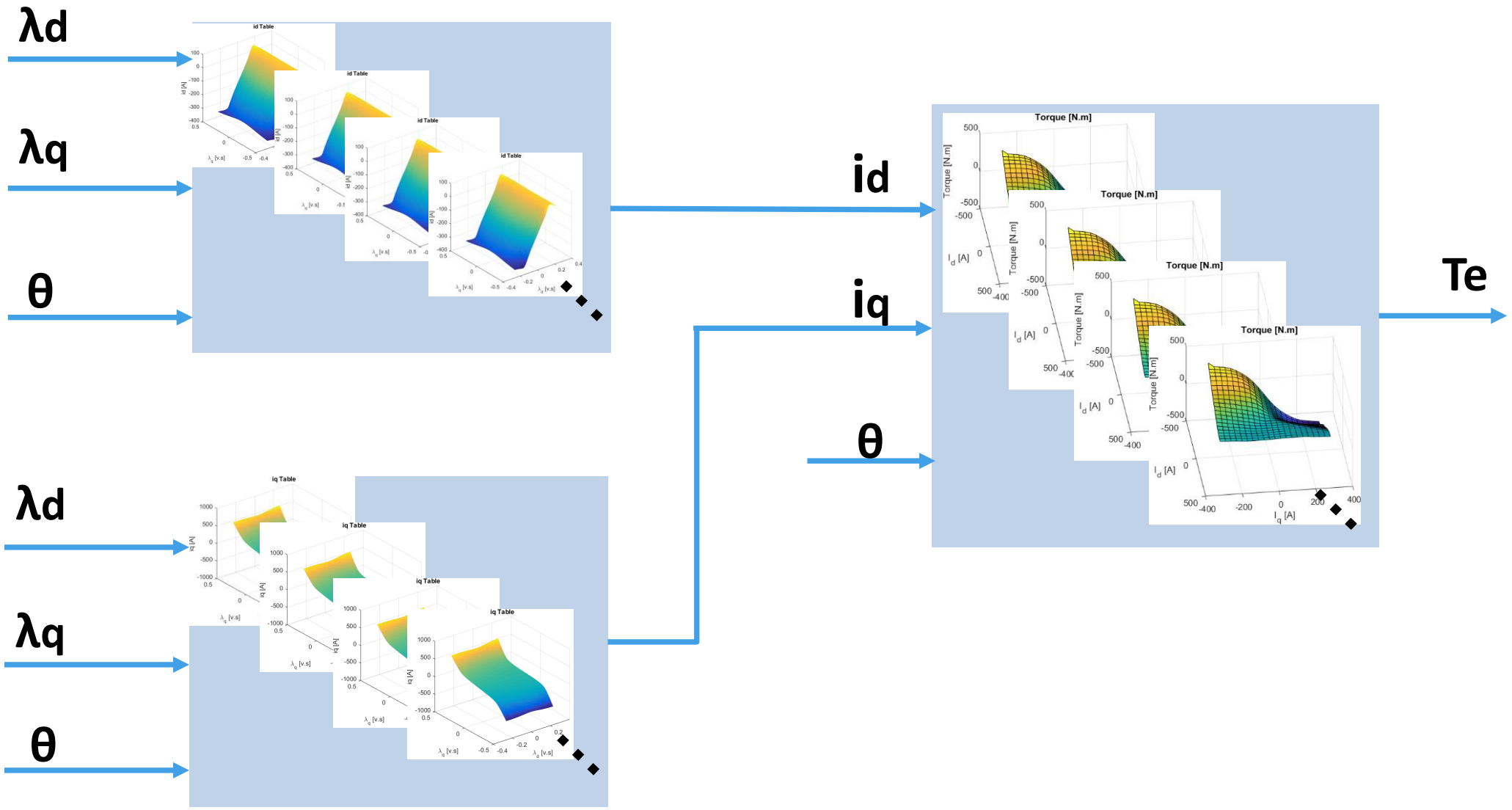
Saturation + Spatial Harmonics Model Structure in Simulink



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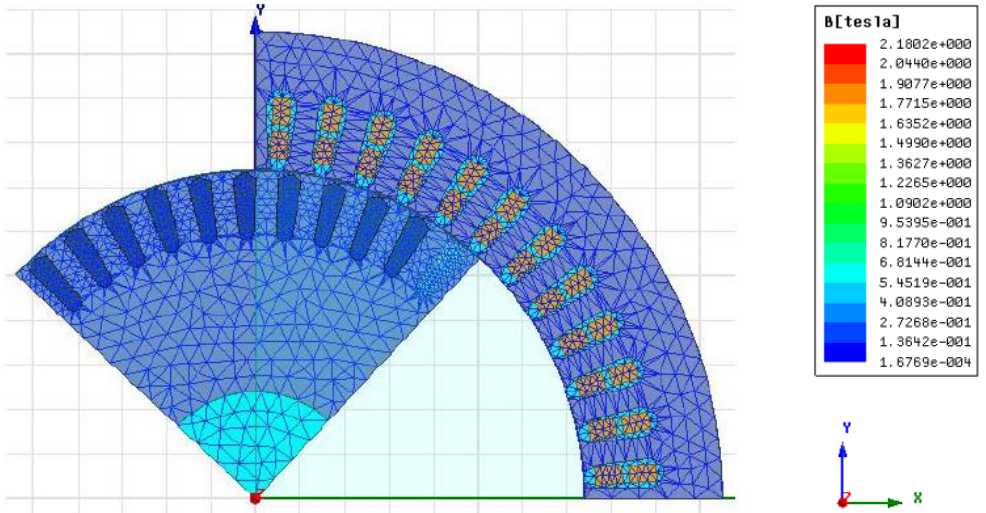
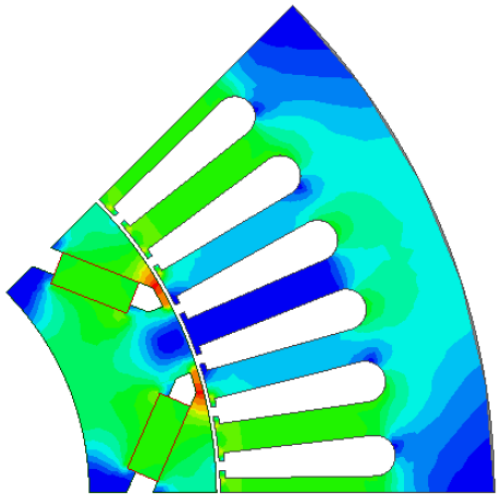
What does ANSYS Maxwell do?

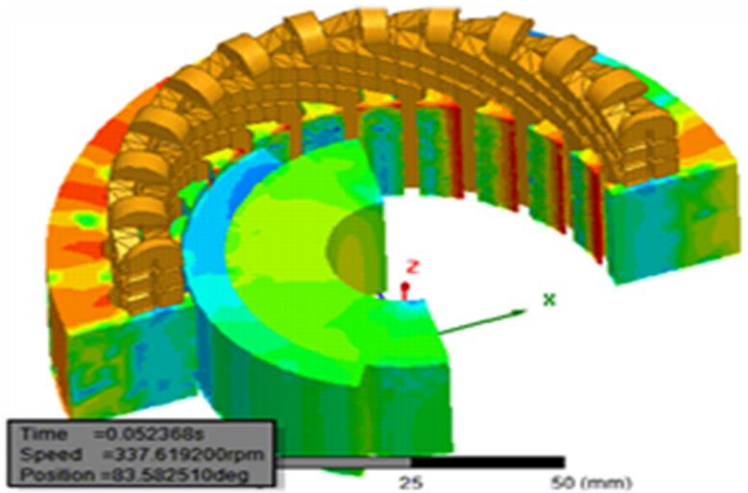
- ANSYS Maxwell is a premier low-frequency electromagnetic field simulation solution which uses the highly accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields. Typical application of Maxwell includes electric machines, transformer, actuator, sensor, etc.



FEA Meshing for Induction Machine



2D FEA PMSM Model



3D FEA PMSM Model

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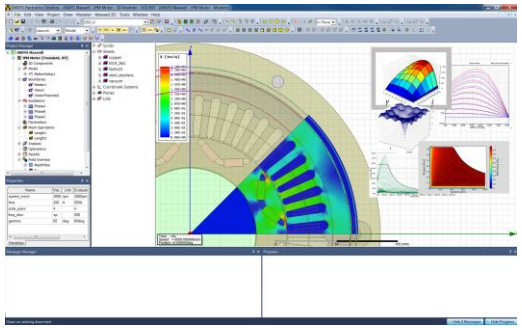

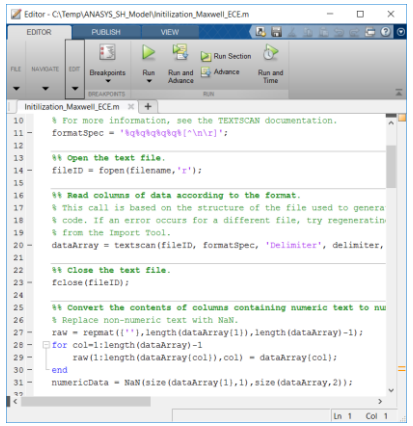

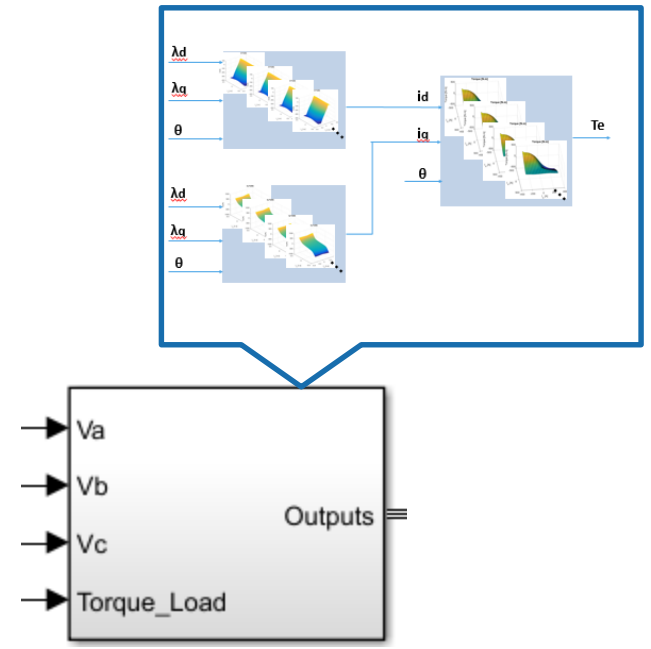

ANSYS Maxwell generates Model_RawData.txt file

Process raw data into proper format through MATLAB scripting

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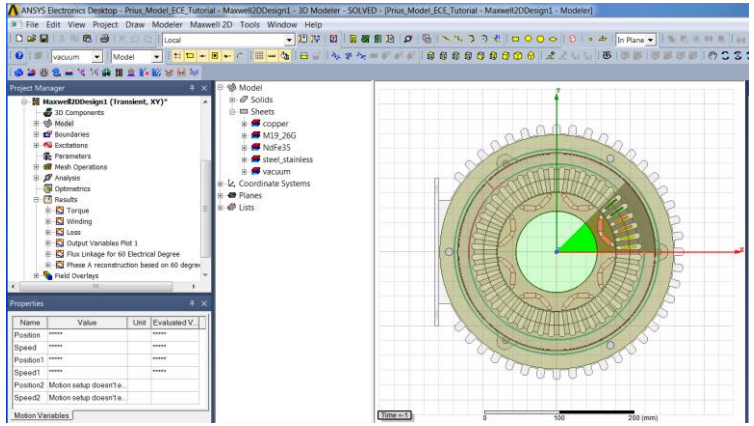
How to obtain raw data for PMSM model by ANSYS Maxwell?
Steps to Generate ECE Model for PMSM

- **Step1: Create Regular FEA Model**



- **Step2: Specify Model Resolution**

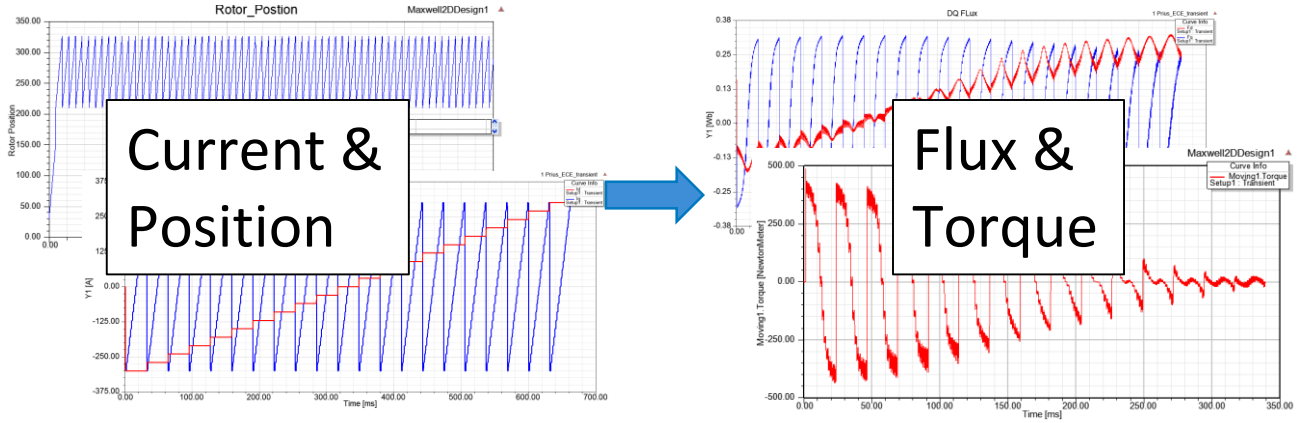
ECE3_Model

	Name	Value	Unit
	DeviceName	ECE3_Model1	
	Windings	PhaseA,PhaseB,PhaseC	
	CurrentSwe...	(30A, 10)	
	PhAngInter...	2	
	Status	Active	

ECER_Model

	Name	Value	Unit
	DeviceName	ECER_Model1	
	RotAngMax	15	deg
	InElecDeg	☐	
	RotAngInter...	15	
	SkewAng	0	deg
	Poles	8	
	Status	Active	

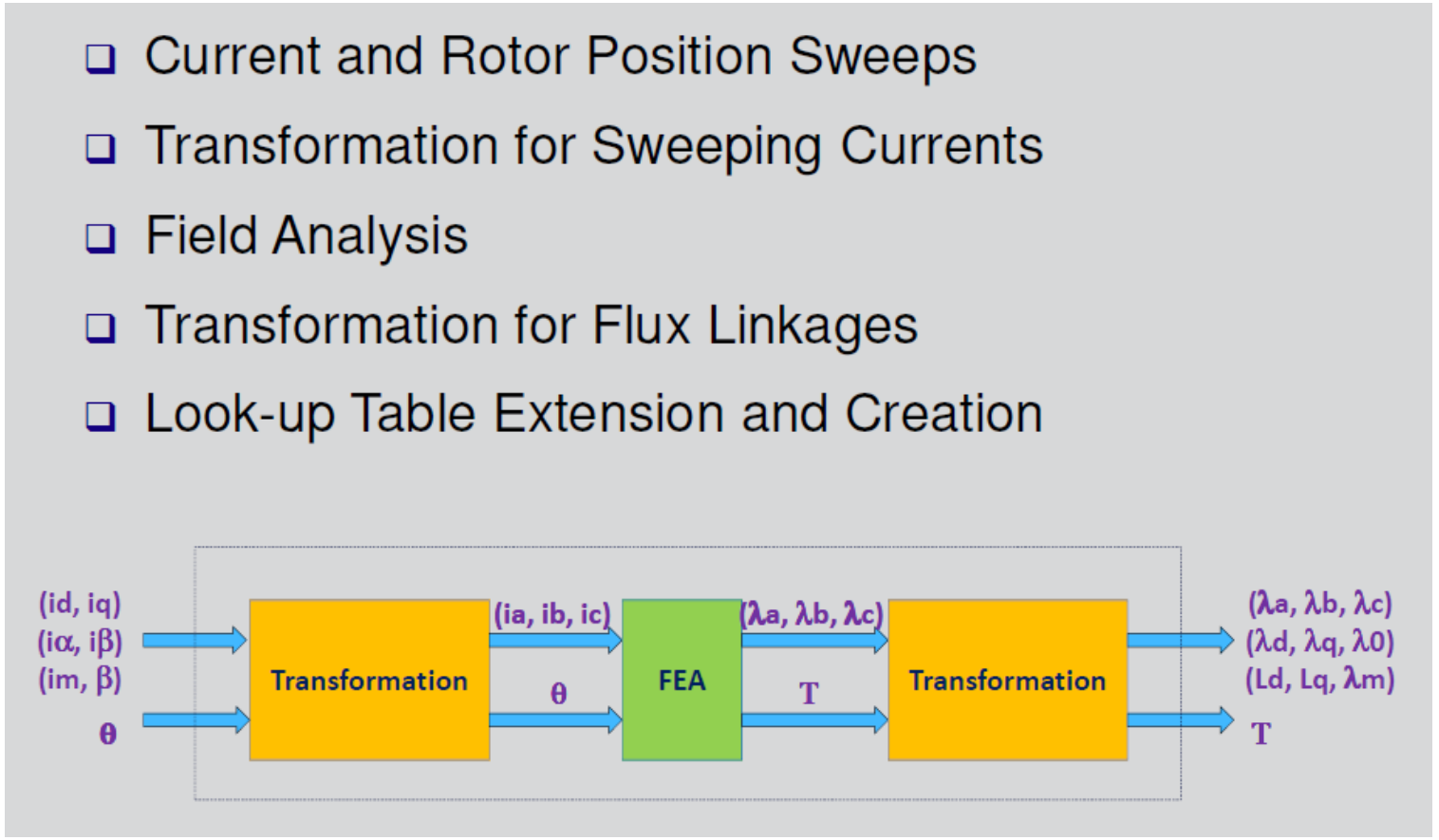
- **Step3: Run FEA Model to Generate Lookup Table**



Model_RawData.txt

What is Equivalent Circuit Extraction (ECE) Model in ANSYS Maxwell

- ECE Model - A circuit model based on a lookup table from precomputed Finite Element Analysis result. It is also known as Reduced Order Model (ROM).

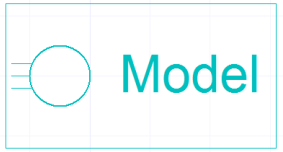


ECE Models Needed for PMSM – ECE3 and ECER
Equivalent Circuit Extraction (ECE)

- Maxwell Circuit Components for Sweep Setup
  - ECEW_Model: ECE one winding model
  - ECE3_Model: ECE three-phase model
  - ECER_Model: ECE rotation model
  - ECEL_Model: ECE linear motion model
  - ECET_Model: ECE transformer model
- ECE Model Formats
  - ECE Simplorer model in file .sml
  - ECE Look-up table for third parties (Saber, ETAS, NI)
  - ECE VHDL model (Future)
  - -- **ECE Simulink Model (.txt)**

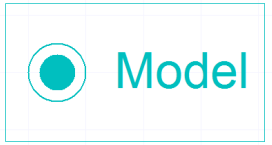
Models Needed for PMSM

ECE3_Model - Setup the sweeping of currents in three-phase windings



ECE3_Model1

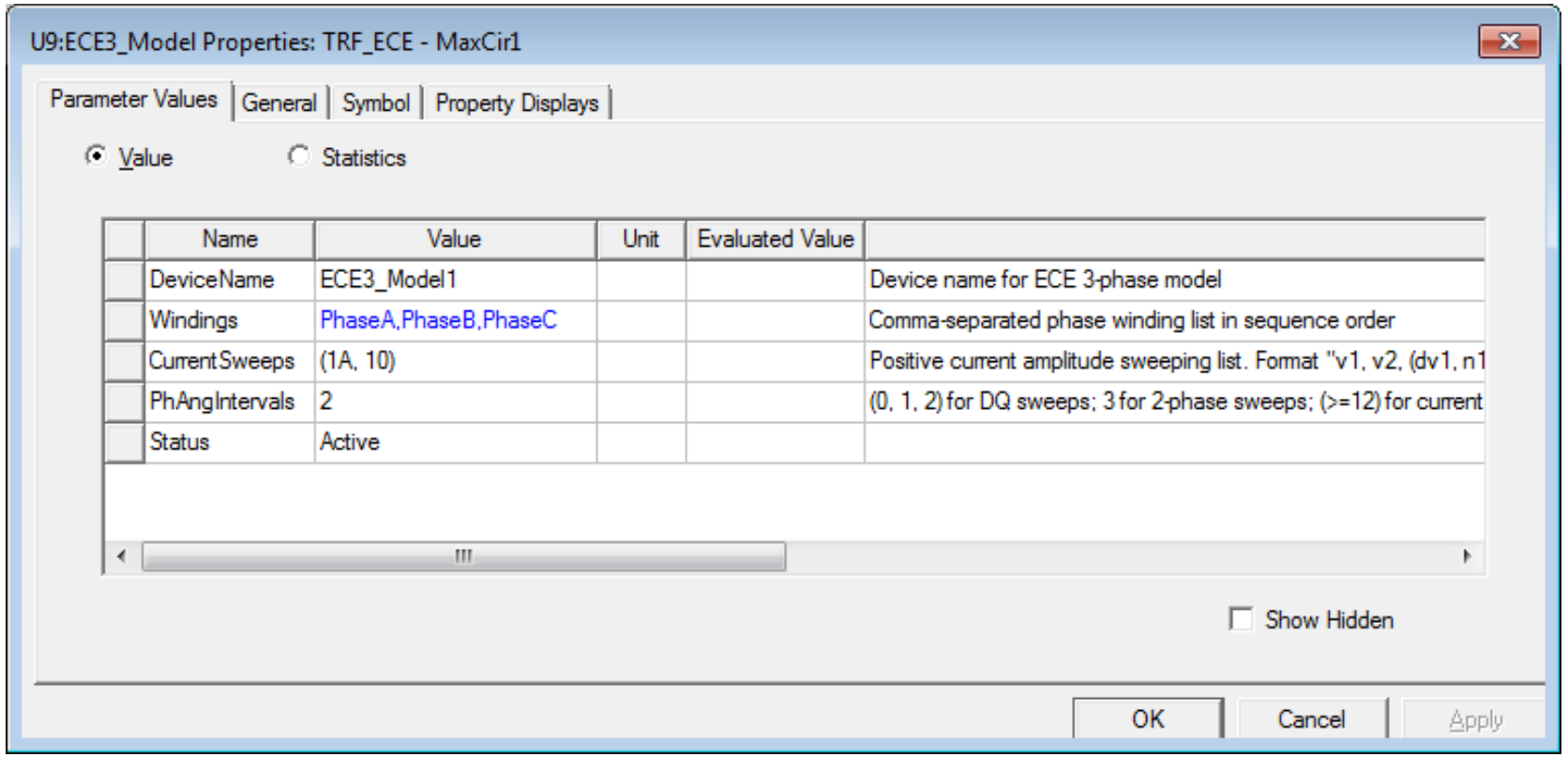
ECER_Model - Setup the sweeping of rotor position

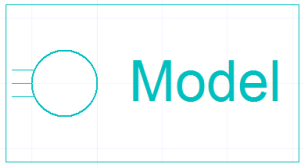


ECER_Model1

ECE3 Model - Setup Sweeping of Current in Three-Phase Winding

- CurrentSweep: Specify Current Range and Resolution
- PhAngIntervals: Choose Current Sweep Coordinate System

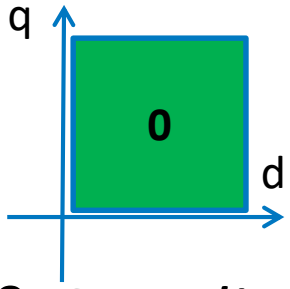


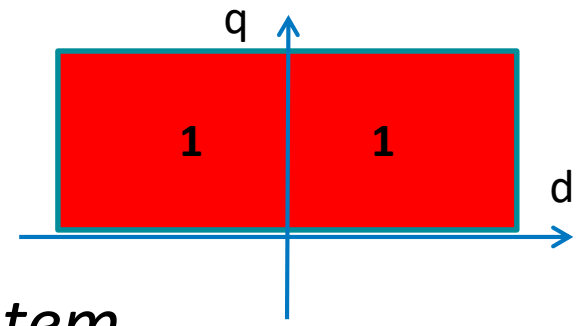


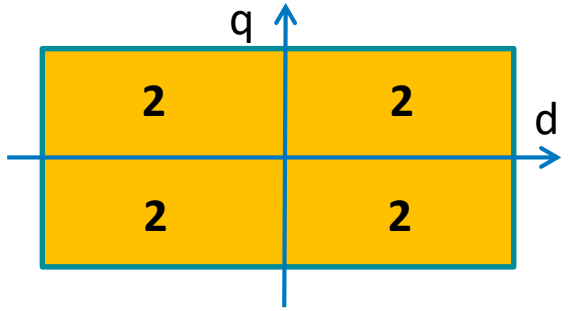
ECE3_Model1

ECE3 Model - Current Sweep Coordinate System Options

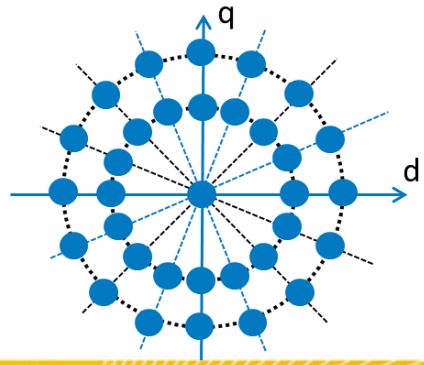
- 1) *DQ Coordinate System*:
- 0: positive d & q.
- 1: positive q, all d.
- 2: all d & q (default)







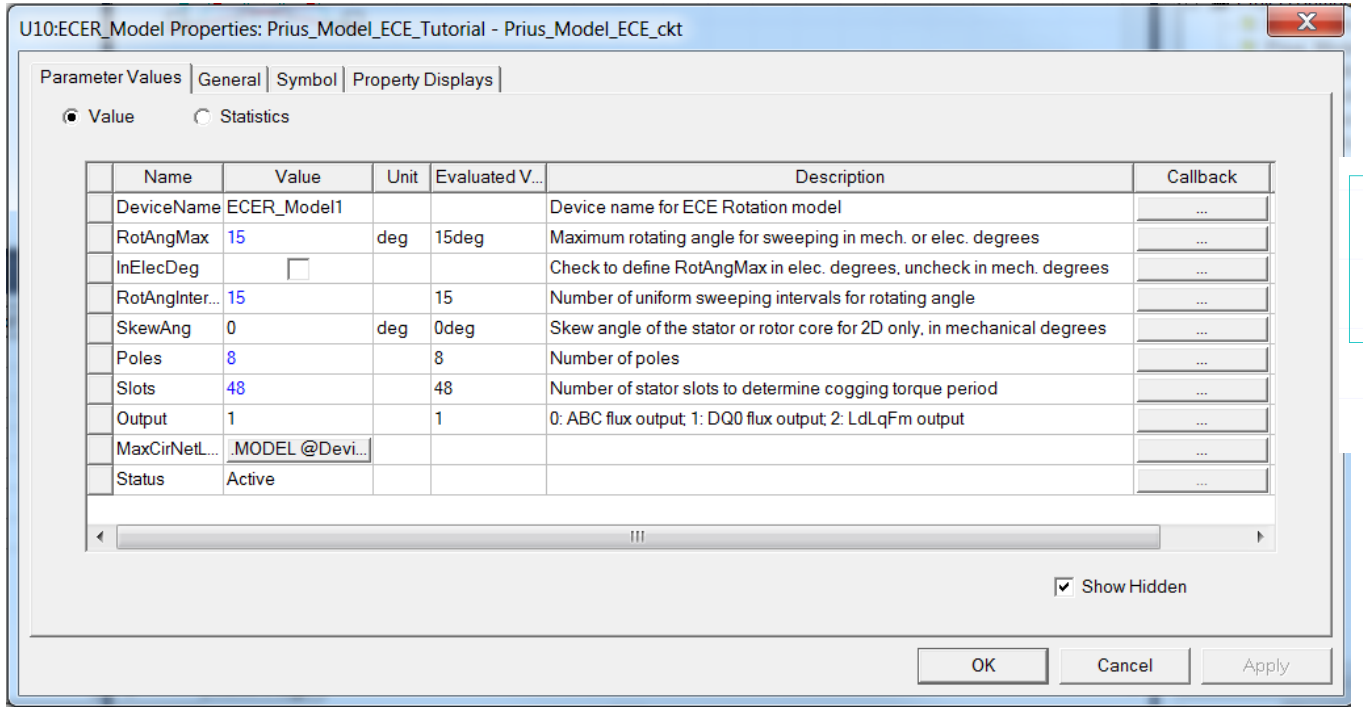
- 2) αβ *Coordinate System*
- 3) Polar DQ *Coordinate System*

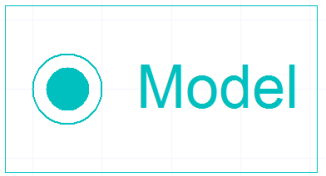


e.g. PhAngIntervals=16

ECER Model - Setup Sweeping of Rotor Position

- RotAngMax: Maximum rotating angle for sweep for each Id-Iq variation. In balanced cases, a 60 elec. degree sweep is sufficient.
- Auto d-axis alignment (no need to manually adjust initial rotor position)
- Slots: enable a separate lookup table for cogging torque.



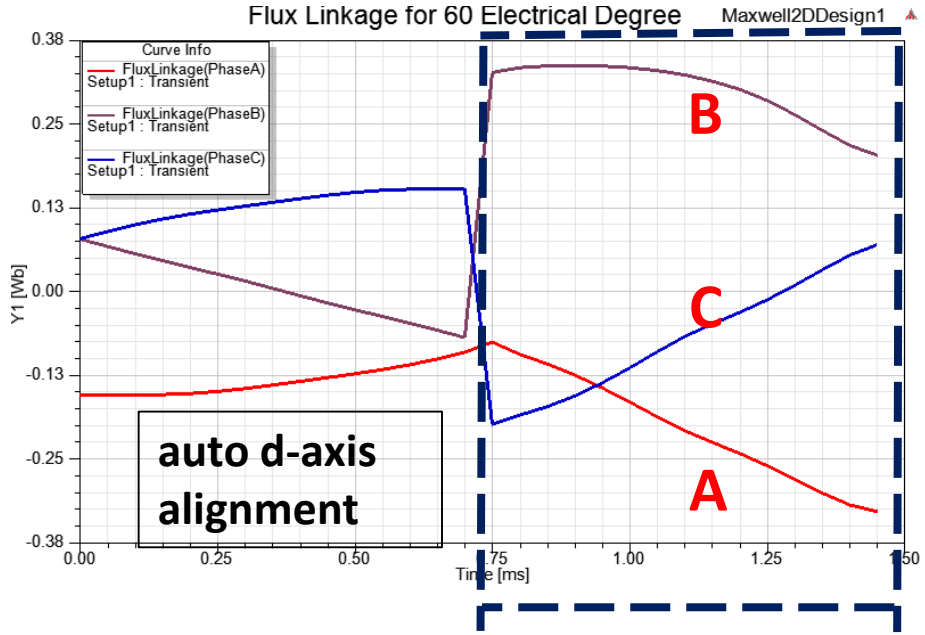


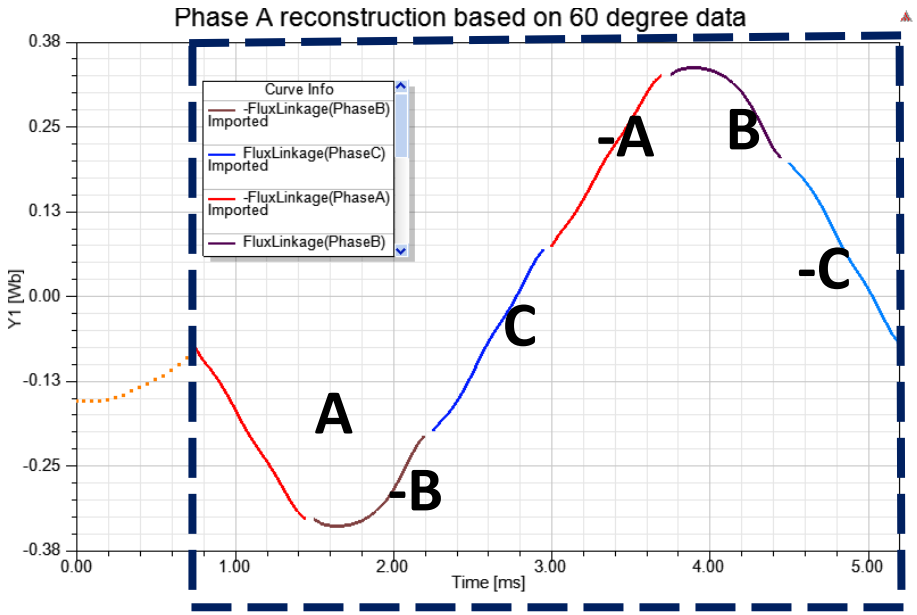
ECER_Model1

Fast Model Generation Technique - Partial Model Sweeping for Symmetric Structure

- 60 Degree Phase Symmetry - Duplicate Data from 60 degree segments:
  PhaseA Reconstruction: A, -B, C, -A, B, -C
  PhaseB Reconstruction: B, -C, A, -B, C, -A
  PhaseC Reconstruction: C, -A, B, -C, A, -B

One 60 elec. Degree Sweep → 360 elec. degree Reconstructed



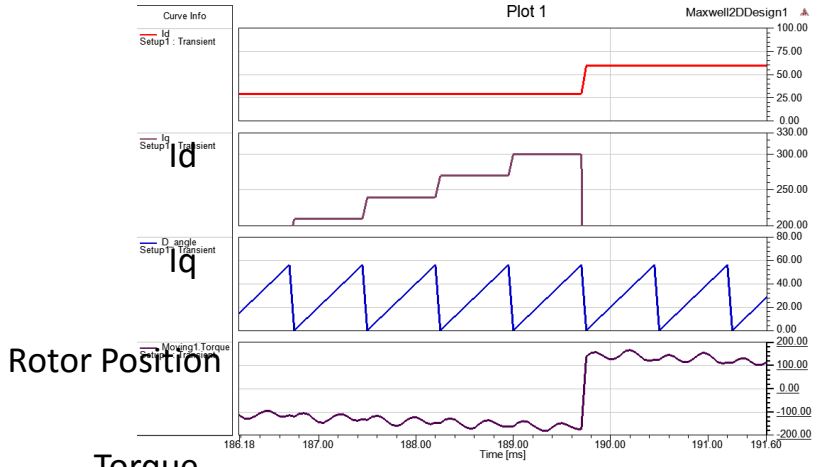


Example – Setups- Takes 3 h 30 min single core

	Name	Value	Unit
	DeviceName	ECE3_Model1	
	Windings	PhaseA,PhaseB,PhaseC	
	CurrentSwe...	(30A, 10)	
	PhAngInter...	2	
	Status	Active	

	Name	Value	Unit
	DeviceName	ECER_Model1	
	RotAngMax	15	deg
	InElecDeg		
	RotAngInter...	15	
	SkewAng	0	deg
	Poles	8	
	Status	Active	

15 deg/mech. = 60 deg/elec. for an 8 pole machine



- Current Sweeps: (10*2+1)^2 = 441 Id-Iq variations

  Id = -300A, -270A, …, -30A,0,30A,…, 270 A, 300A

  Iq = -300A, -270A, …, -30A,0,30A,…, 270 A, 300A

- Rotor Position Sweep: 0 deg (d-axis), 1 deg, 2 deg, 3 deg,…,14deg. 15 rotor positions.
- For each Id-Iq variation, 15 rotor positions will be swept to reconstruct a 360 elec. degree sweep.
- Total number of time steps calculated = 441 * 15 = 6615. (About 2 second/step)

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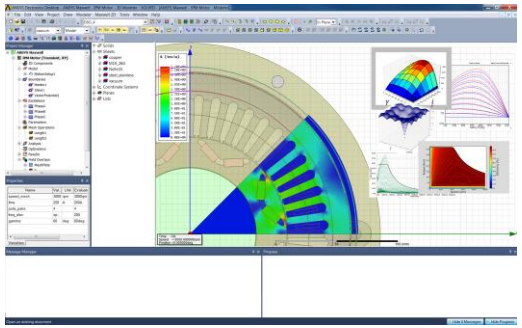
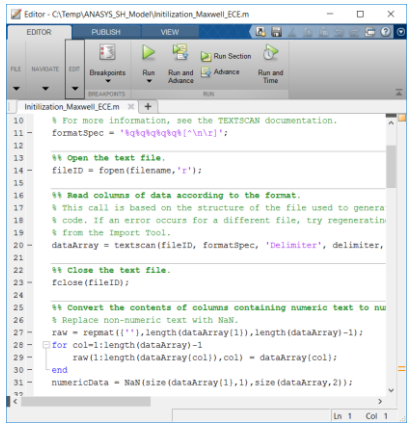
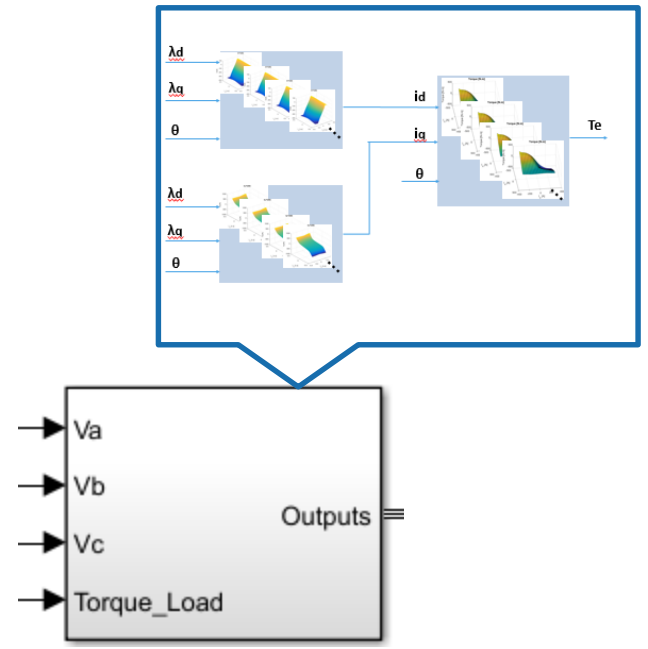






ANSYS Maxwell generates Model_RawData.txt file

Process raw data into proper format through MATLAB scripting

Bring processed data into Simulink saturation + harmonics motor model structure

Four Steps in Maxwell_to_MATLAB Script.m

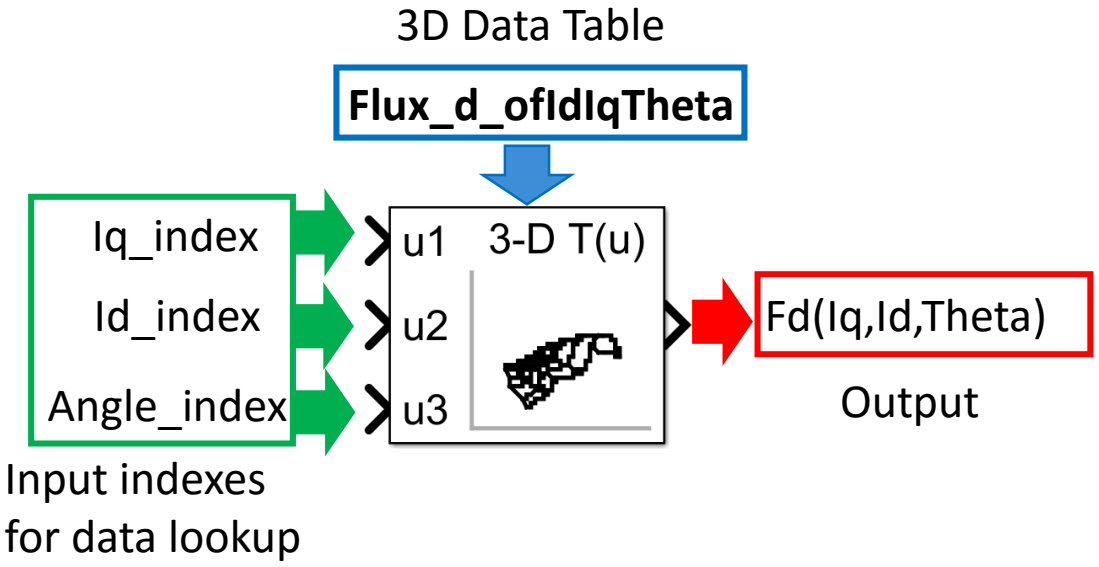
- **Step 1: Import Original Raw Data from Maxwell ECE Model.**
- **Step 2: Create (Id, Iq, Angle) to (Flux D, Flux Q, Torque) Lookup Table (3D Lookup Table) based on the raw data.**
- **Step 3: Create inverse lookup table to get current from flux input.**

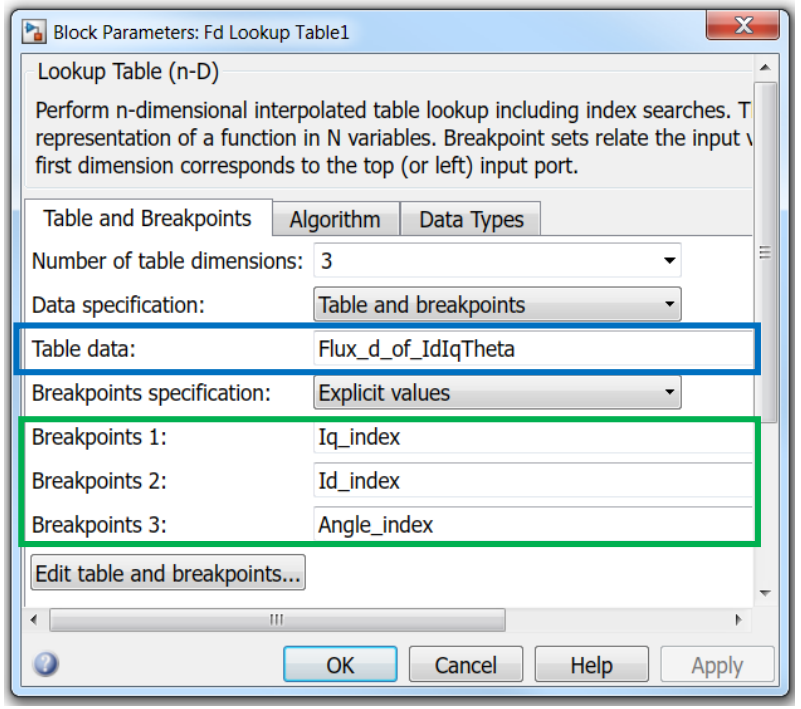
  (Flux D, Flux Q, Angle) to (Id, Iq, Torque) Lookup.
- **Step 4: Provide additional Parameters.**

  Initial rotor angle, phase resistance, rotor inertia, friction coefficient.

n-D Lookup Table in Simulink

- There are three Tabs in the n-D Lookup Table block: 1) Table and Breakpoints; 2) Algorithm and 3) Data Types.
- As an example, the screen shots below show a Table and Breakpoints setup for d-axis flux 3D lookup table. Iq_index, Id_index, Angle_index and Flux_d_ofIdIqTheta are defined in Workspace already.

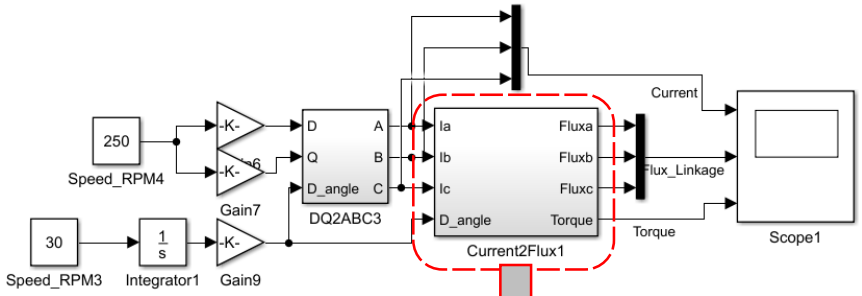


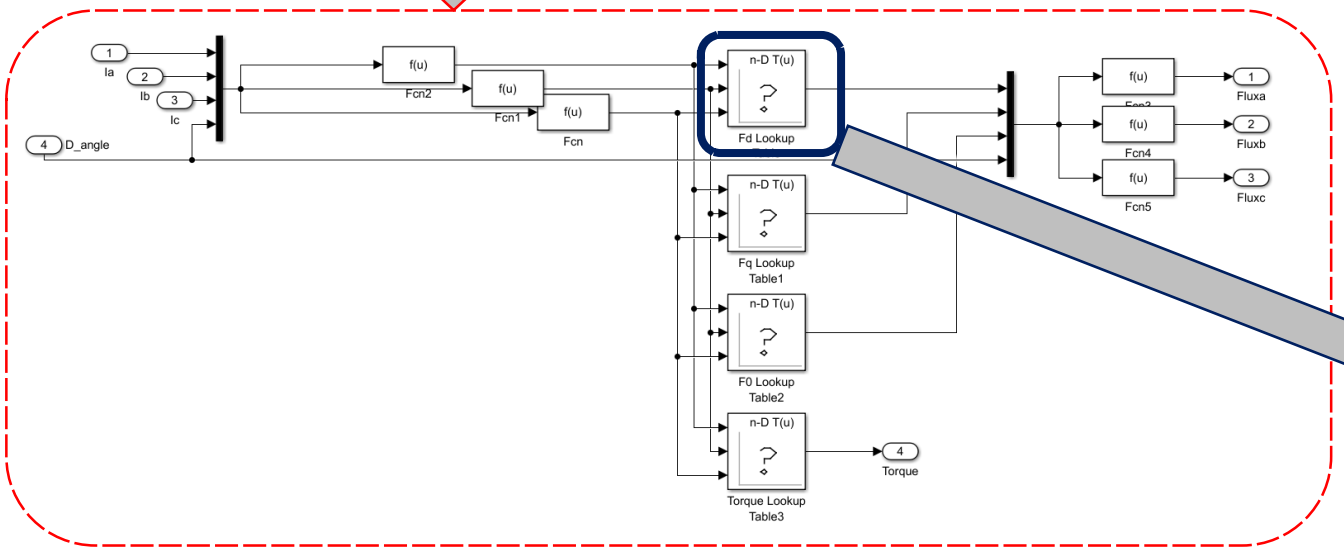


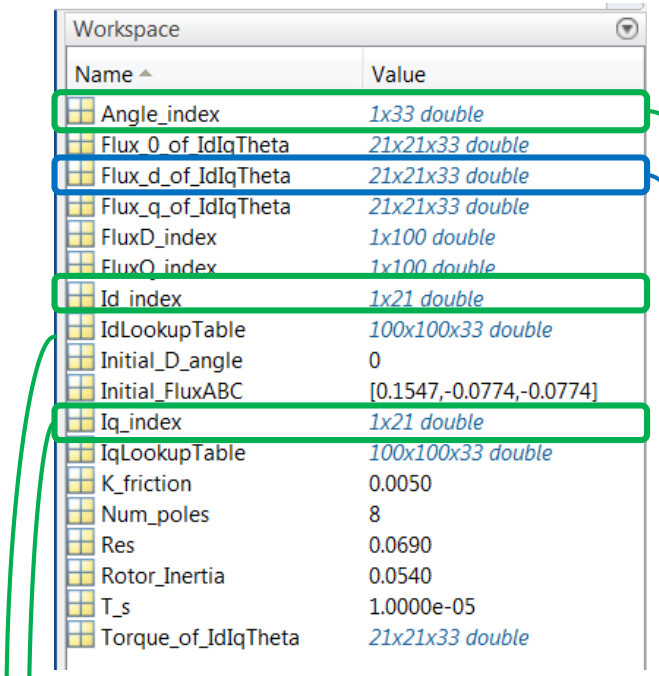
Set up n-D Lookup Table in Simulink

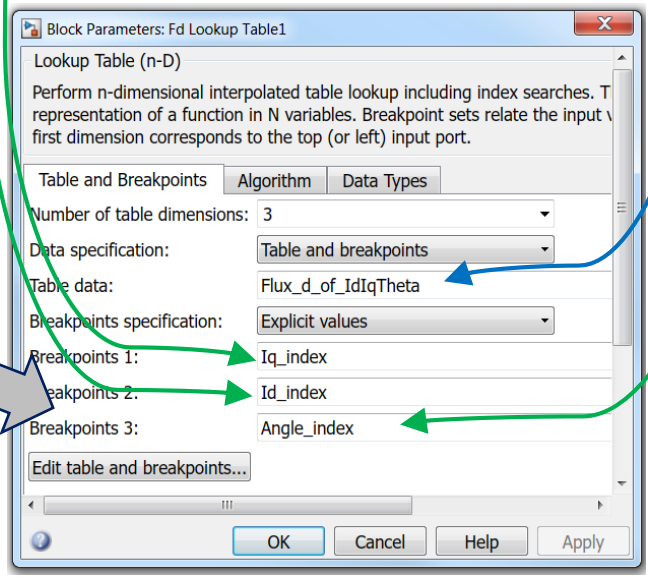
- **Model Structure.**

Current to Flux Lookup - Maxwell Direct Result
Current Excitation, Frequency = 2 Hz, 30 rpm
No Mechancial Dynamic









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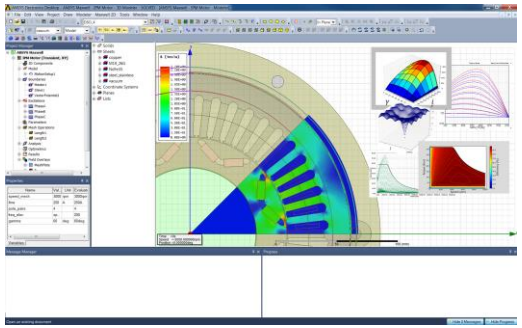

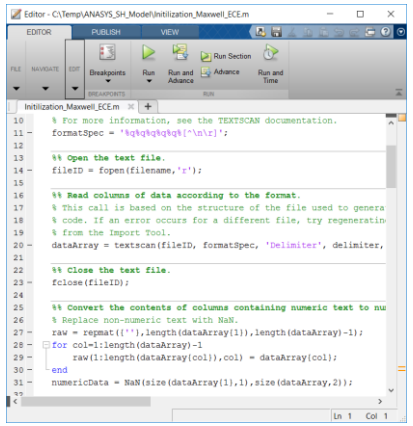

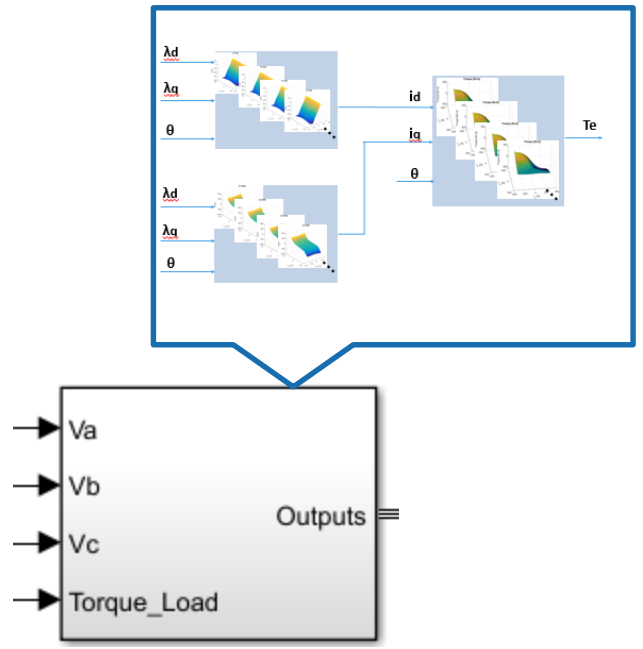

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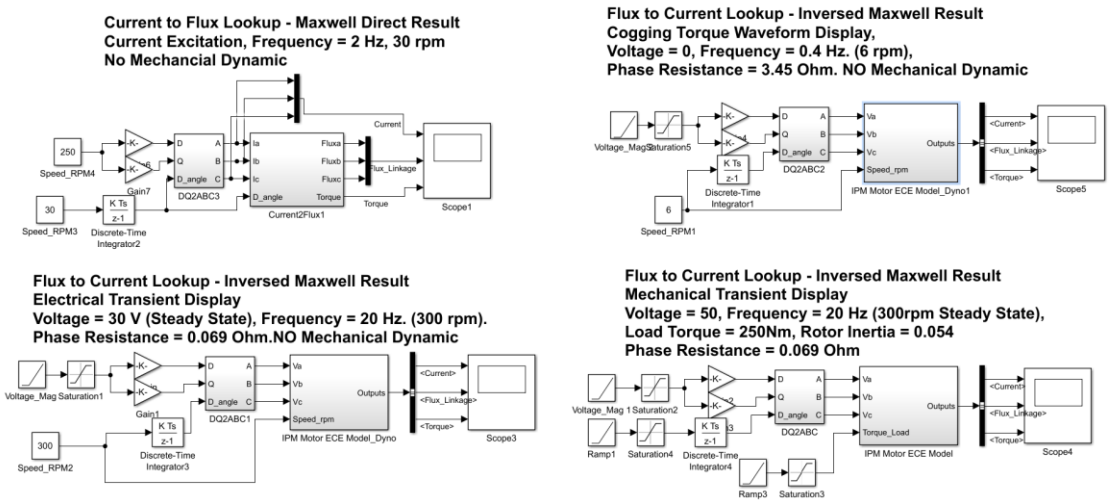
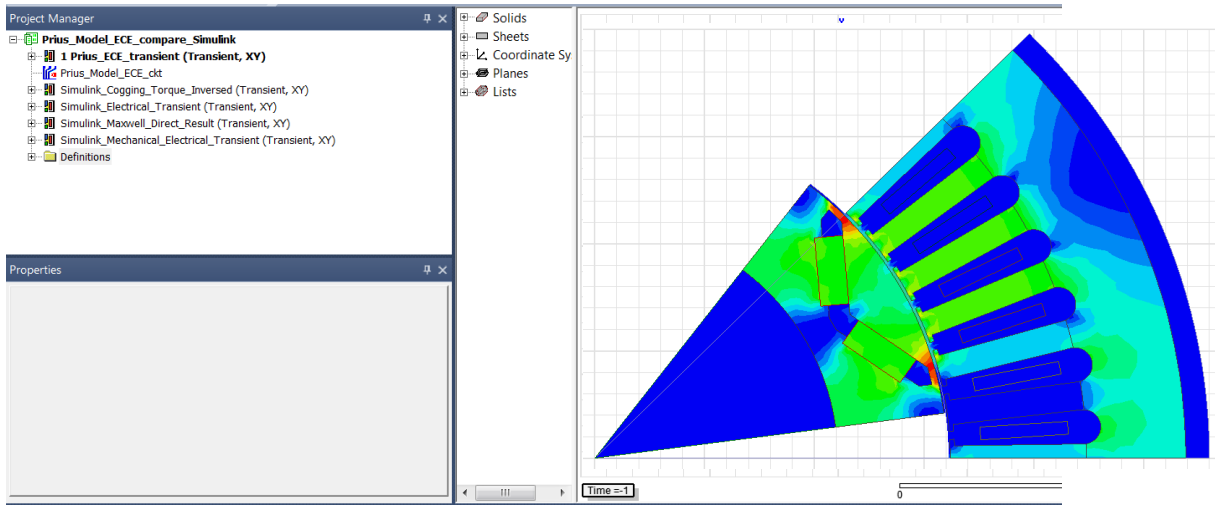
Comparison between Simulink model and Maxwell FEA model:
Four cases to compare **current, flux, and torque** waveform.

1. Open circuit
2. Sinusoidal winding current input
3. Voltage input under constant rotor speed
4. Voltage input with mechanical dynamic (Starting of PMSM)

Simulink model

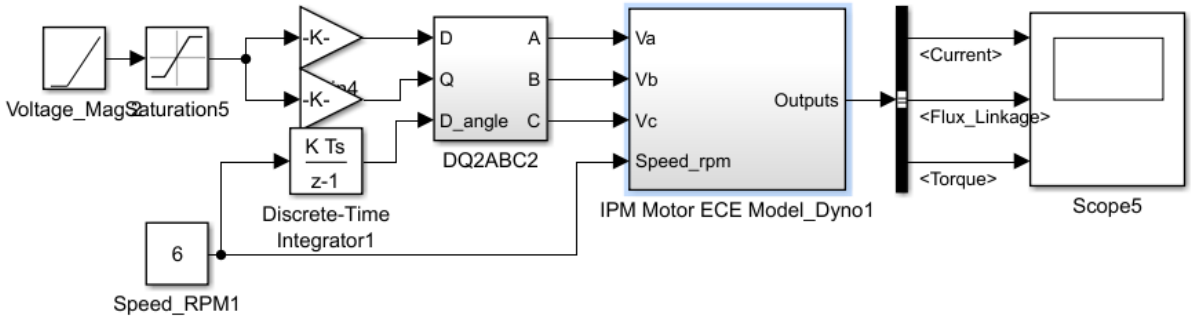


Maxwell FEA model



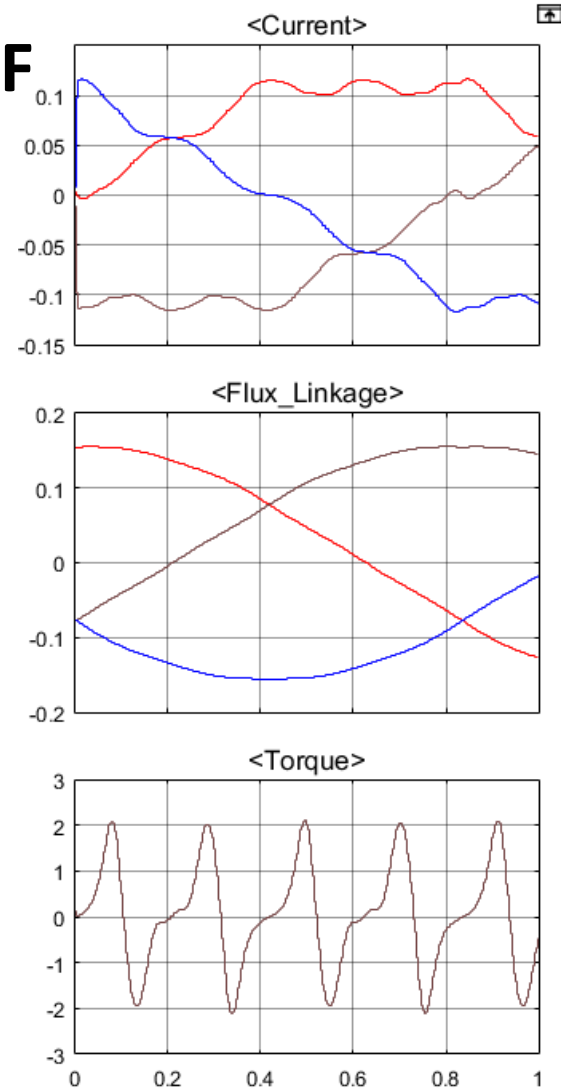
Example – Prius IPM motor – Open circuit – Cogging torque & Back EMF

Flux to Current Lookup - Inversed Maxwell Result
Cogging Torque Waveform Display,
Voltage = 0, Frequency = 0.4 Hz. (6 rpm),
Phase Resistance = 3.45 Ohm. NO Mechanical Dynamic

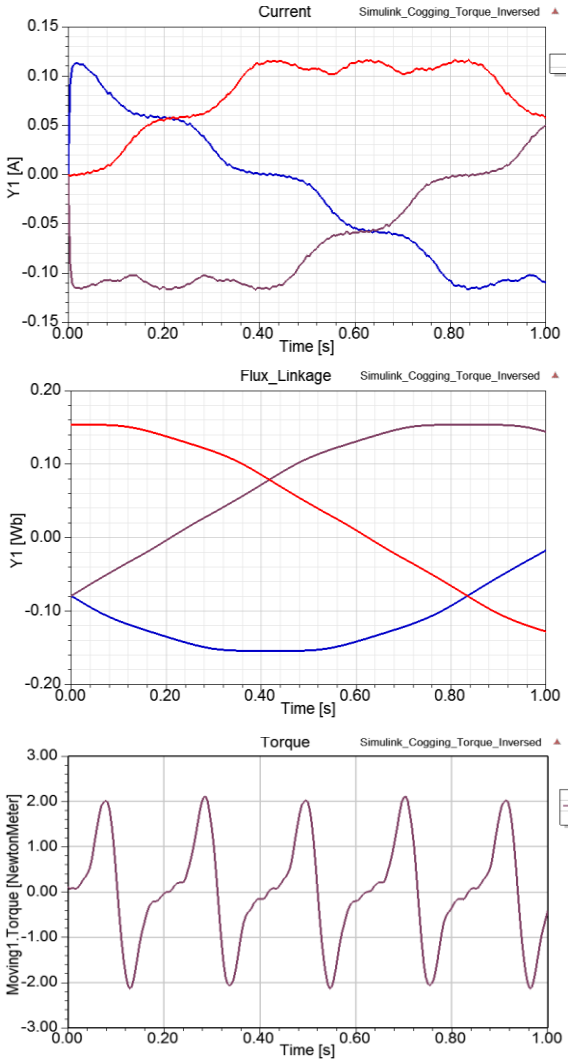


- Simulink result is compared with Maxwell result. The results are very close.
- Inverse lookup is successful.

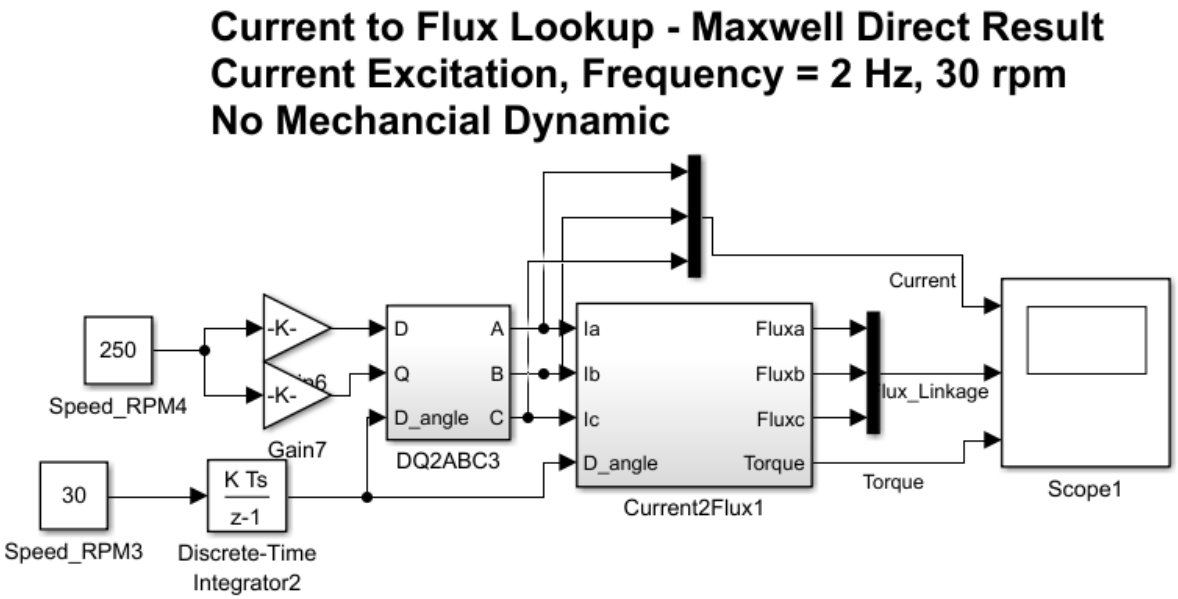
Simulink Result



Maxwell Result

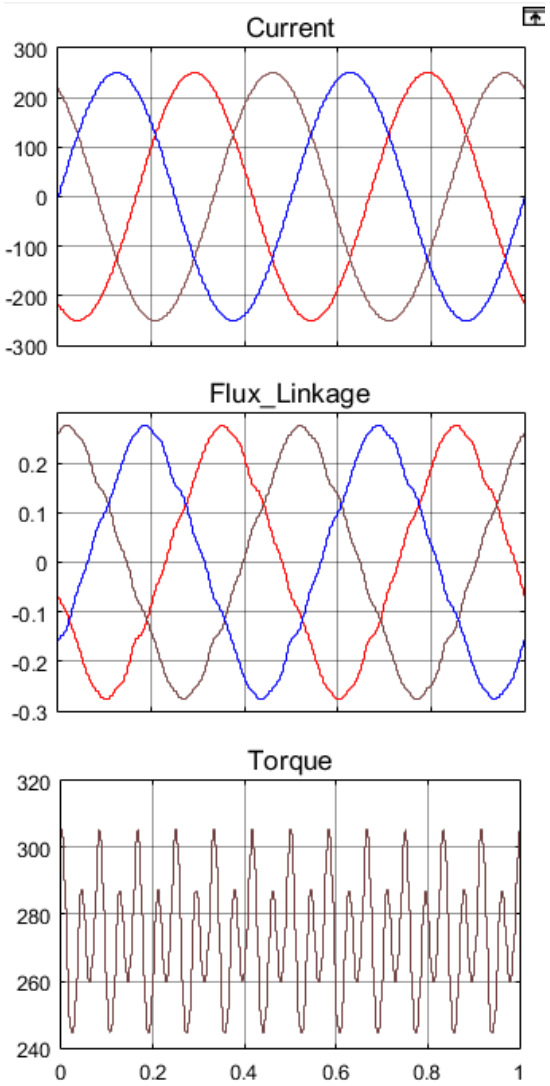


Sinusoidal winding current input Torque ripple

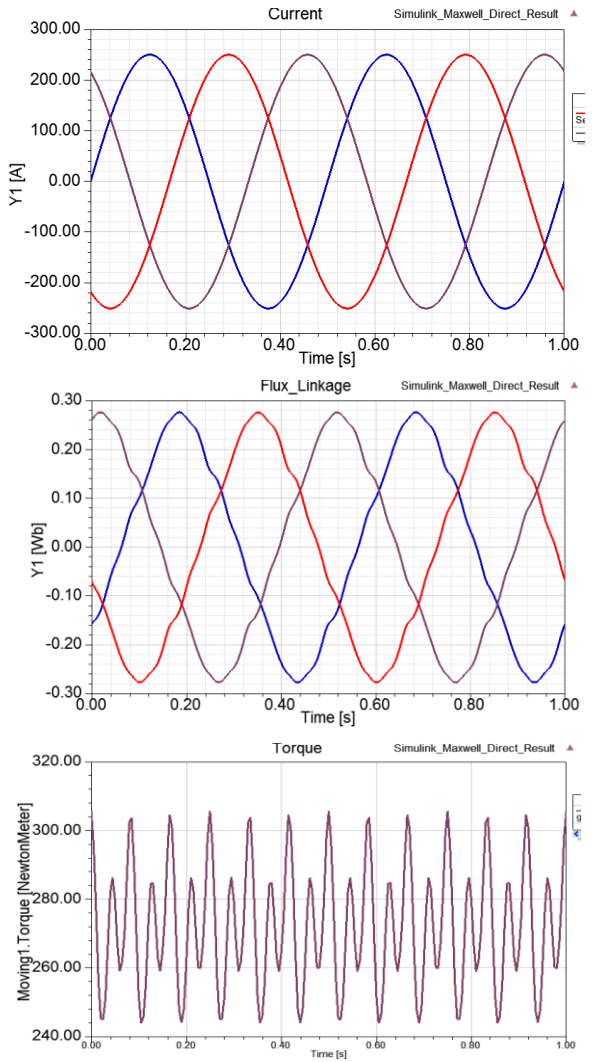


- Simulink result is compared with Maxwell result. The results are identical.
- Data transfer is successful.

Simulink Result

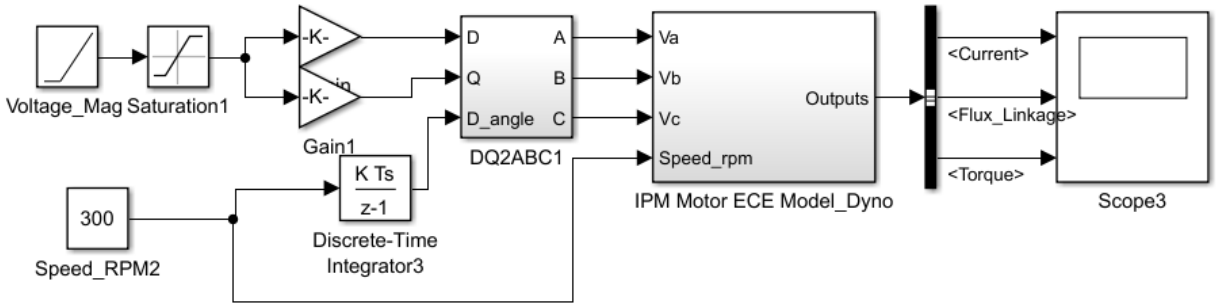


Maxwell Result



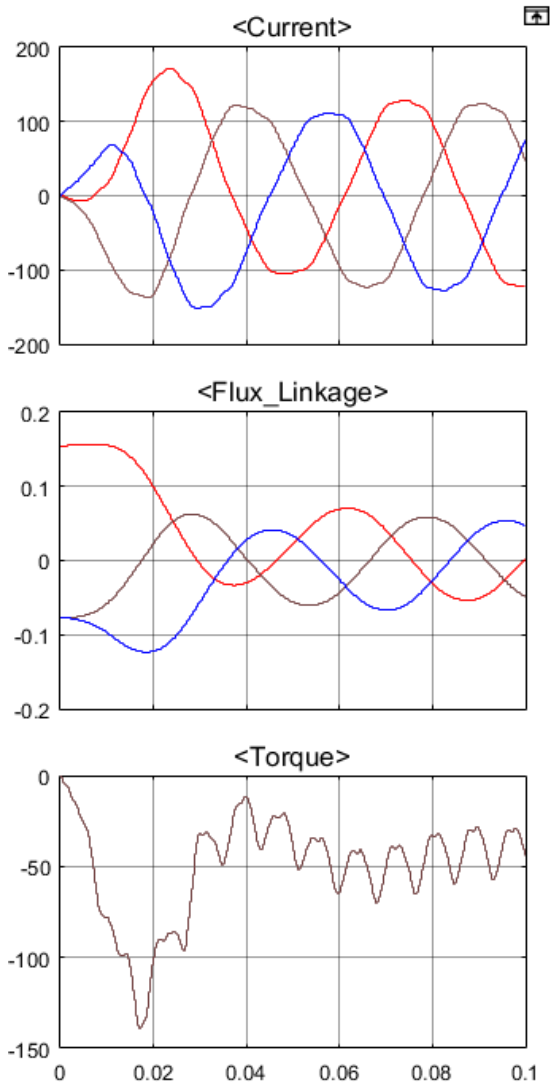
Voltage input under constant rotor speed Electrical Transient

Flux to Current Lookup - Inversed Maxwell Result
Electrical Transient Display
Voltage = 30 V (Steady State), Frequency = 20 Hz. (300 rpm).
Phase Resistance = 0.069 Ohm.NO Mechanical Dynamic

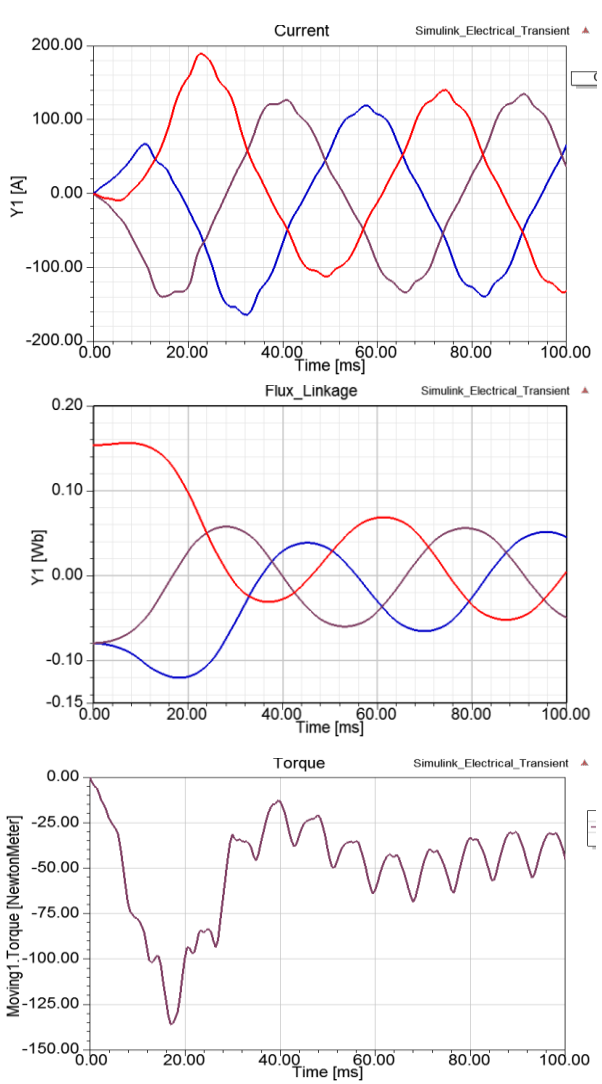


- Simulink result is compared with Maxwell result. The results are very close.
- Motor phase resistance is considered.

Simulink Result

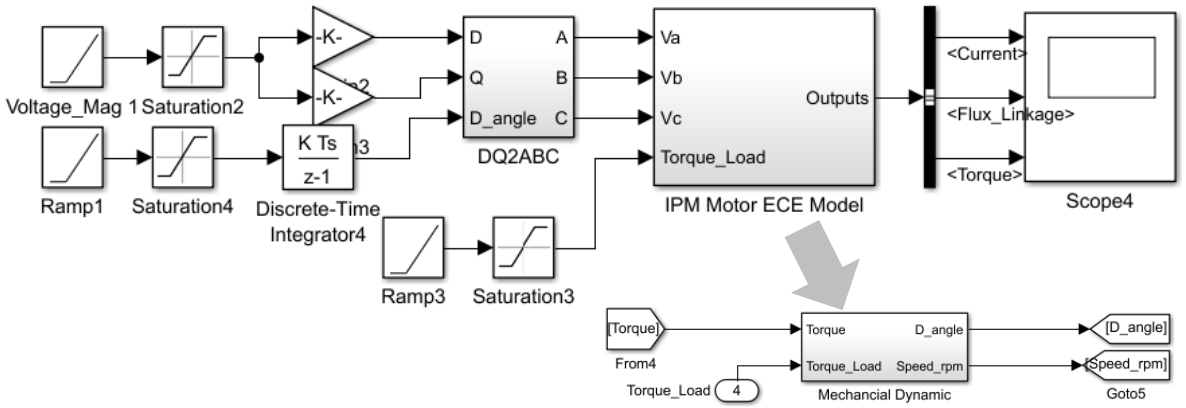


Maxwell Result



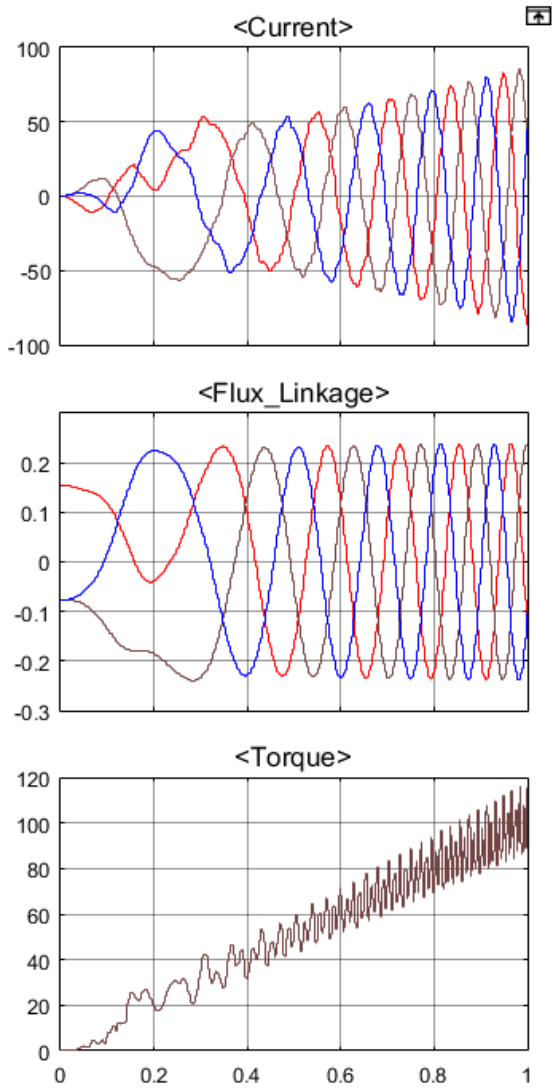
Voltage input with mechanical dynamic Mechanical & Electrical Transient

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

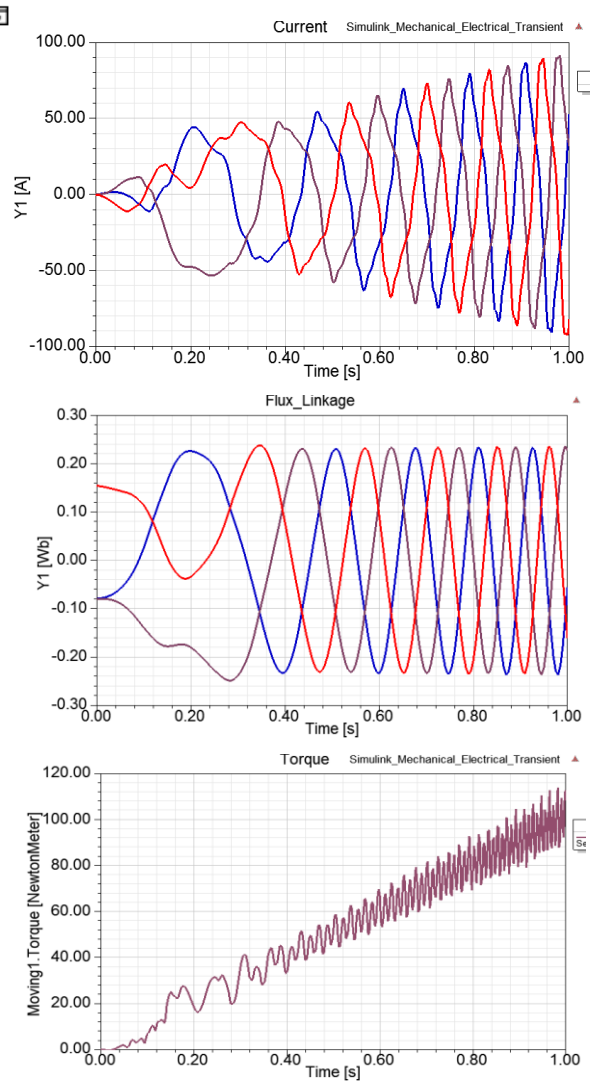


- Simulink result is compared with Maxwell result. The results are very close.
- Mechanical dynamic is considered.

Simulink Result



Maxwell Result



Key Takeaways:

- ANSYS Maxwell can perform sweeping and generate raw machine data.
- Raw machine data can be processed and brought into Simulink for high fidelity machine modeling.
- High fidelity machine model is an accurate representation of the actual machine and it runs really fast in Simulink.