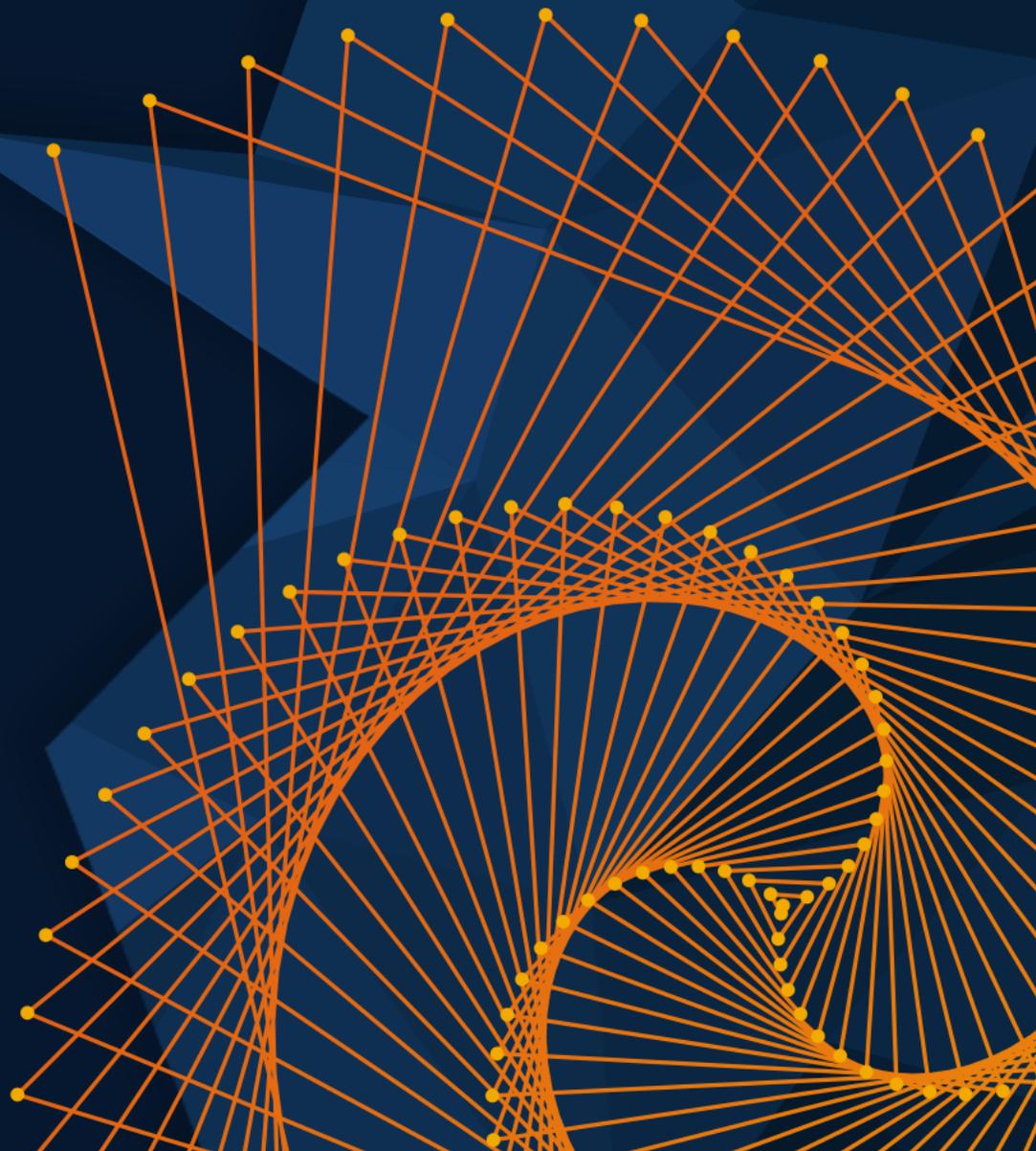


MATLAB EXPO

5月28日, 2024 | 北京

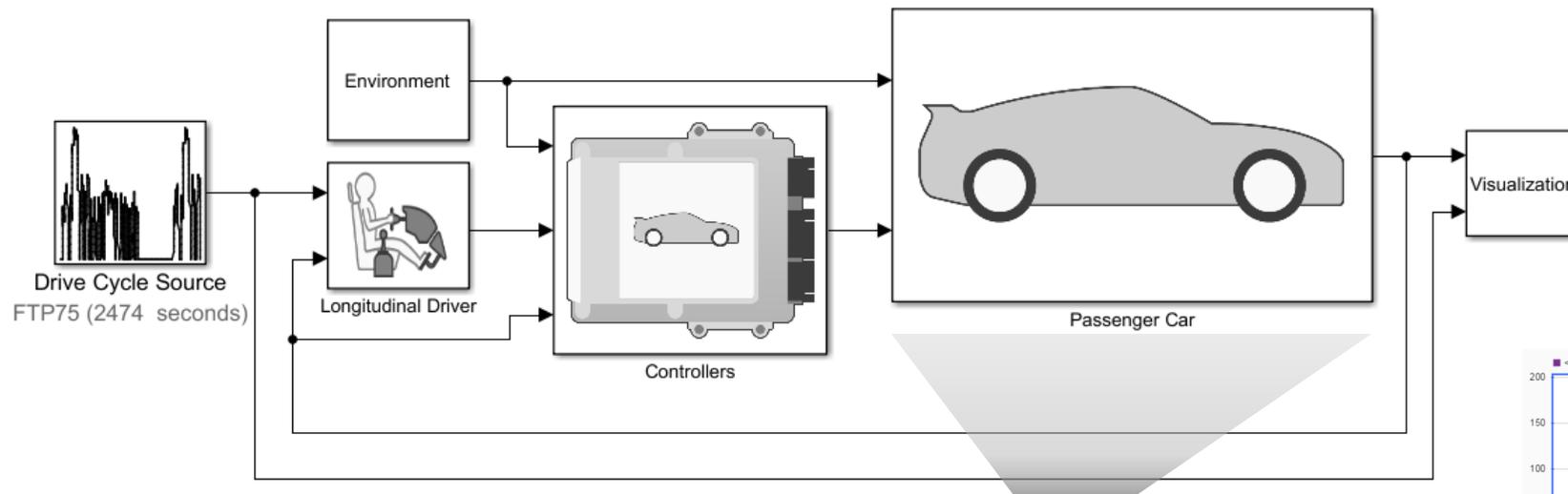
基于模型设计助力高效电机驱动控制算法的仿真和实现

徐浩, MathWorks高级咨询顾问

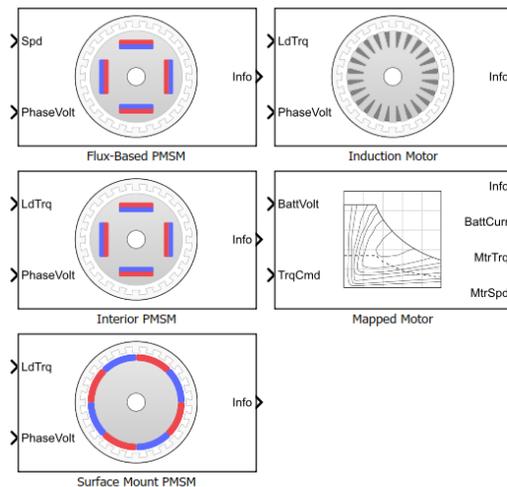
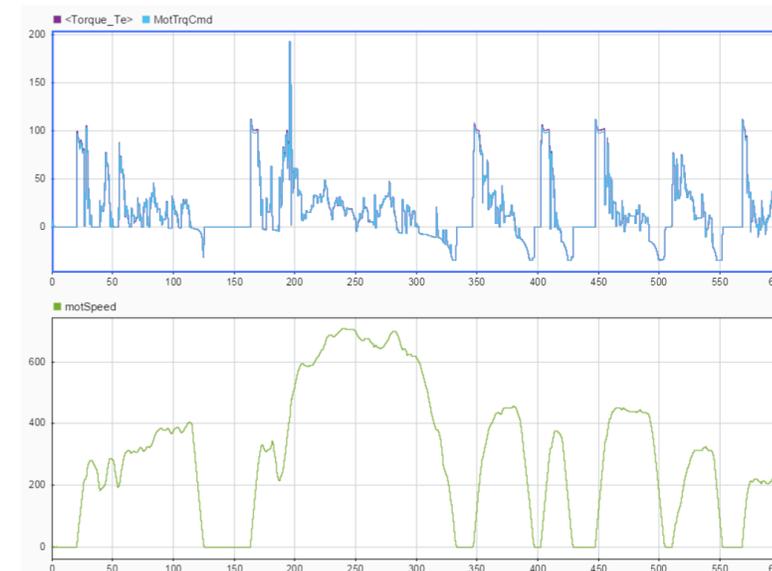


电动动力总成的核心：电机

- 组件选择?
- 组件选型?
- 权衡研究?



- 详细的组件建模和控制设计?



电动汽车电机控制开发面临的挑战

如何实现有效的弱磁控制？



EV电机工程师

如何获取电机参数来开发电机模型？



建模工程师

如何生成高效的代码并移植到不同的硬件？



嵌入式工程师

如何调节控制环增益以实现性能？

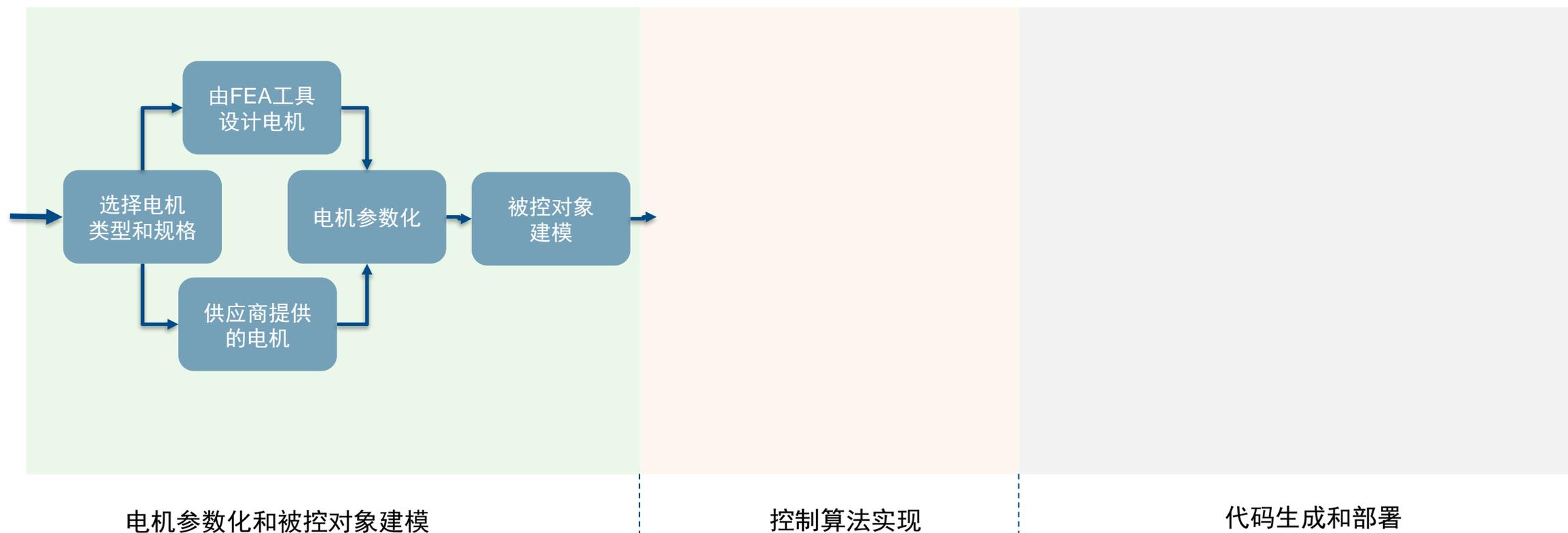


控制工程师

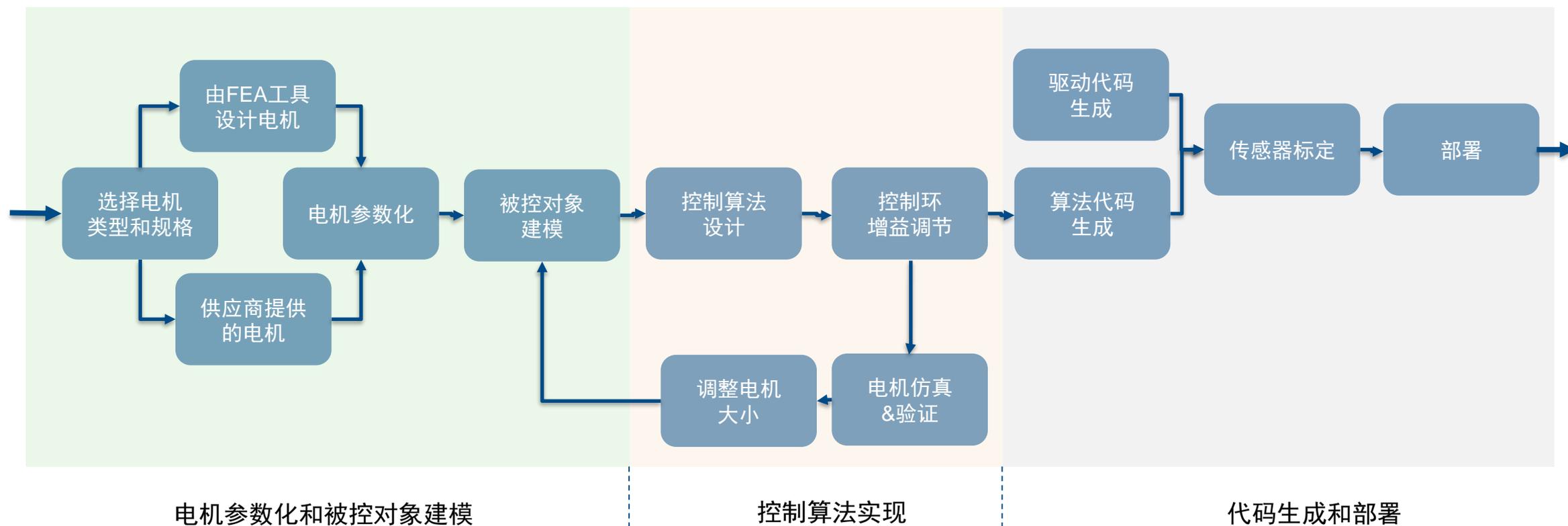
建议的电动车驱动电机控制软件开发流程



建议的电动车驱动电机控制软件开发流程



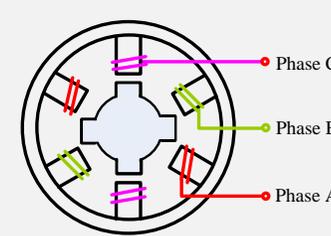
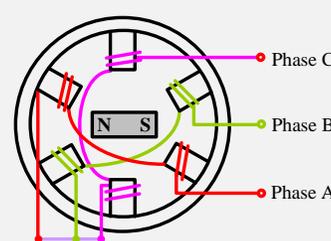
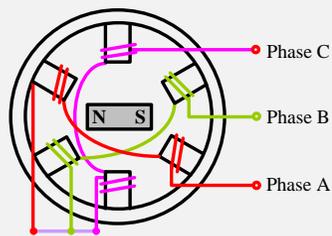
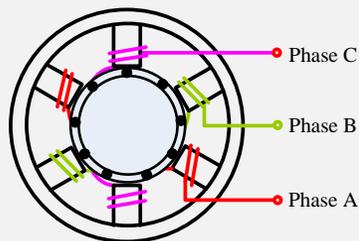
建议的电动车驱动电机控制软件开发流程



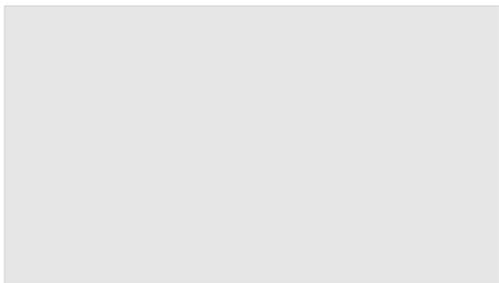
电机选型

- 选择电机类型和规格
- 电机参数化
- 被控对象建模

电机概览



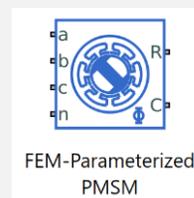
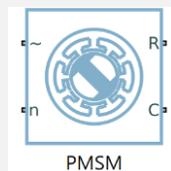
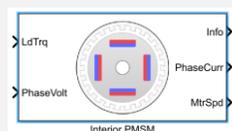
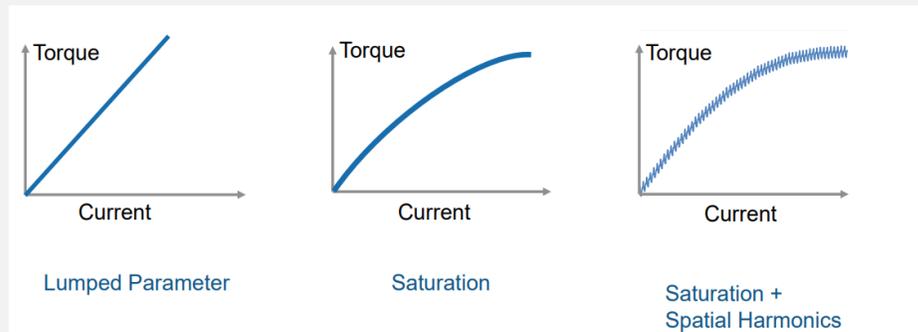
异步电机(IM)	无刷电机(BLDC)	永磁同步电机 (PMSM)	开关磁阻电机(SRM)
Advantages			
<ul style="list-style-type: none"> - Low material cost/ kg - Robust, reliable, Simple Control - Less maintenance 	<ul style="list-style-type: none"> - Efficient, reliable - High Power Density and High torque at low speed 	<ul style="list-style-type: none"> - Low noise, smooth operation - High performance and efficiency over operating range 	<ul style="list-style-type: none"> - Simple and robust construction - Low cost, long constant power range
Disadvantages			
<ul style="list-style-type: none"> - Low efficiency, low power factor specially at light loads, Heavy, High Copper loss 	<ul style="list-style-type: none"> - Higher torque ripples and cogging torque leads to vibration, noise and poor position control 	<ul style="list-style-type: none"> - High Cost - Demagnetizing risk - Requires complex control 	<ul style="list-style-type: none"> - High noise, torque ripples - Complex Control - High Switching losses
Industry Examples			
Tesla model X, Toyota RAV4 EV, Renault Zoe	Ather, Toyota Prius	Tesla Model S, Chevrolet Bolt, Hyundai Kona Electric	Jaguar I-PACE Concept, Ford Fiesta EV Prototype



电机参数化和模型保真度

- 选择电机类型和规格
- 电机参数化
- 被控对象建模

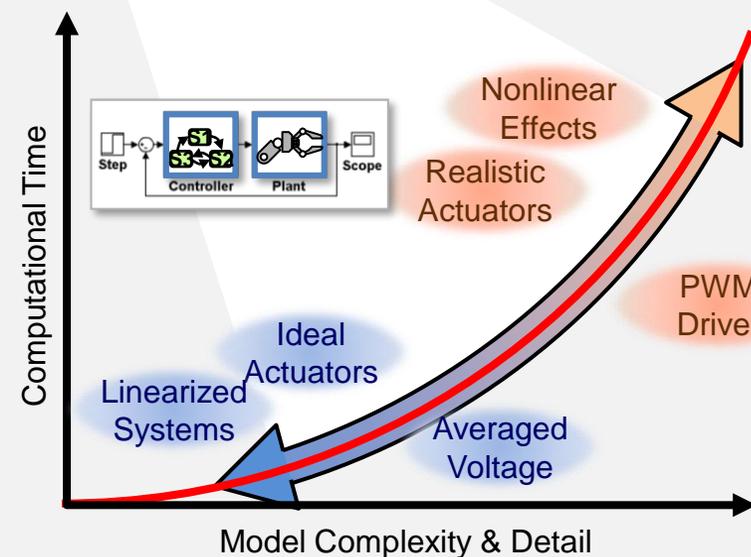
Motor Model Fidelity Level



Motor Control Blockset

Simscape Electrical

Computational Time vs. Model Complexity



电机参数化和被控对象建模

Motor Parameterization

被测电机

电机和测功机

电机FEA模型

选择电机类型和规格

电机参数化

被控对象建模

Estimate Motor Parameters Using Motor Control Blockset Parameter Estimation Tool

Motor Control Blockset™ provides a parameter estimation tool that estimates the motor parameters accurately. Use the estimated motor parameters to simulate the motor model and design the control system. Therefore, the simulation response with the estimated parameters for the motor model is close to the behavior of the motor under test.

The parameter estimation tool determines these motor parameters for a Permanent Magnet Synchronous Motor:

Motor parameters	Units
Phase resistance (R_s)	Ohm
d and q axis inductances (L_d and L_q)	Henry
Back-EMF constant (K_e)	Vpk_LL/krpm (where Vpk_LL is the peak voltage line-to-line measurement)
Motor inertia (J)	Kg.m ²
Friction constant (f)	N.m.s

The parameter estimation tool accepts the minimum required inputs, runs tests on the target hardware, and displays the estimated parameters.

来自产品规格书
或电机试验

集总参数模型

Generate Parameters for Flux-Based PMSM Block

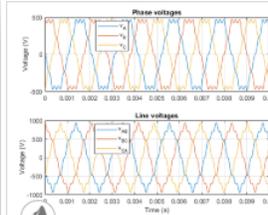
Using MathWorks tools, you can create lookup tables for an interior permanent magnet synchronous motor (PMSM) controller that characterizes the d -axis and q -axis current as a function of d -axis and q -axis flux.

To generate the flux parameters for the Flux-Based PMSM block, follow these workflow steps. Example script `CreatingIdqTable.m` calls `gridfit` to model the current surface using scattered or semi-scattered flux data.

Workflow	Description
Step 1: Load and Preprocess Data	Load and preprocess this nonlinear motor flux data from dynamometer testing or finite element analysis (FEA): <ul style="list-style-type: none"> d- and q- axis current d- and q- axis flux Electromagnetic motor torque
Step 2: Generate Evenly Spaced Table Data From Scattered Data	Use the <code>gridfit</code> function to generate evenly spaced data. Visualize the flux surface plots.
Step 3: Set Block Parameters	Set workspace variables that you can use for the Flux-Based PM Controller block parameters.

来自测功机试验

饱和效应模型



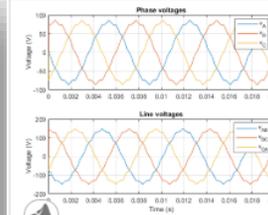
Import IPMSM Flux Linkage Data from ANSYS Maxwell

Import a motor design from ANSYS® Maxwell® into a Simscape™ simulation.

[Open Model](#)

来自FEA工具如 ANSYS Maxwell, JMAG, Motor-CAD

饱和效应+空间谐波模型



Import IPMSM Flux Linkage Data from Motor-CAD

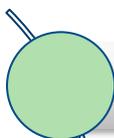
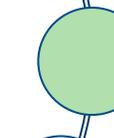
Import a motor design from Motor-CAD into a Simscape™ simulation.

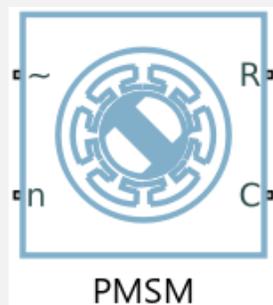
[Open Model](#)

参数化有助于电机建模，从而获取电机动态，帮助我们进行控制设计

电机参数化和被控对象建模

根据电机规格书定义电机参数

-  选择电机类型和规格
-  电机参数化
-  被控对象建模



Block Parameters: PMSM

Settings Description

NAME	VALUE
Modeling option	No thermal port
Selected part	<click to select>
Main	
Electrical connection	Composite three-phase ports
Winding type	Wye-wound
Modeling fidelity	Constant Ld, Lq, and PM
> Number of pole pairs	6
> Permanent magnet flux linkage parameterization	Specify flux linkage
> Permanent magnet flux linkage	0.03 Wb
> Stator parameterization	Specify Ld, Lq, and L0
> Stator d-axis inductance, Ld	0.00019 H
> Stator q-axis inductance, Lq	0.00025 H
> Stator zero-sequence inductance, L0	0.00016 H
> Stator resistance per phase, Rs	0.013 Ohm
Zero sequence	Include
Rotor angle definition	Angle between the a-phase magnetic axis
Iron Losses	
Mechanical	
Initial Targets	
Nominal Values	

Block Parameterization Manager: PMSM

SELECT FORMAT

Apply all Reset all

Manufacturer: All

PARAMETERIZE

Select part

Part number	Manufacturer	Rated Speed, rpm	Pole Pairs
BSM132C-8200AA	ABB_BALDOR	1800	4
BSM33C-5177MHQ	ABB_BALDOR	1800	4
BSM50N-133	ABB_BALDOR	4000	2
BSM50N-275	ABB_BALDOR	2000	2
BSM63N-133	ABB_BALDOR	4000	2
HDS100-0206A	ABB_BALDOR	3000	5
HDS130-0817B	ABB_BALDOR	2000	5
HDS130-1829B	ABB_BALDOR	2900	18.0000
HDS180-2540B	ABB_BALDOR	4000	25.0000
HDS180-4876B	ABB_BALDOR	7600	48.0000
HDS180-1072A	ABB_BALDOR	1900	0.6000
		3000	5

Compare selected part with block

Parameter name	Parameterization	Override datasheet value	Part value:BSM132C
Main>Number of pole pairs	Datasheet derived	<input checked="" type="checkbox"/>	4
Main>Permanent magnet flux linkage	Datasheet derived	<input checked="" type="checkbox"/>	0.229230859562701
Main>Torque constant	Datasheet derived	<input checked="" type="checkbox"/>	0.916923438250803
Main>Back EMF constant	Datasheet derived	<input checked="" type="checkbox"/>	0.916923438250803
Main>Stator d-axis inductance, Ld	Datasheet derived	<input checked="" type="checkbox"/>	0.00115
Main>Stator q-axis inductance, Lq	Datasheet derived	<input checked="" type="checkbox"/>	0.00115
Main>Direct-axis current vector, iD	Parameter not set	<input type="checkbox"/>	[-200 0 200]
Main>Quadrature-axis current vector, iQ	Parameter not set	<input type="checkbox"/>	[-200 0 200]

电机参数化和被控对象建模

基于实验测试估计电机参数

选择电机类型和规格

电机参数化

被控对象建模

- 运行在目标上测试
- 提供参考示例模型
- 支持有/无速度传感器
- 支持PMSM和异步电机

Board Selection

DRV8305 and F28379D Launchpad

Communication Port

Serial Setup

The COM port has to match your board
For F28069 Launchpad, set Baudrate to 5.625e6
For F28379D Launchpad, set Baud rate to 5e6

Required Inputs

Nominal Voltage: 24 V

Nominal Current: 7.1 A (rms value)

Nominal Speed: 4000 rpm

Pole pairs: 4

Input DC Voltage: 20 V

Hall Offset: 0.28 Per Unit Position

Note: Press Ctrl+D to update the workspace

Hall Offset: For Hall offset calculation open required model for the hardware
[mcb_pmsm_hall_offset_f28069m](#)
[mcb_pmsm_hall_offset_f28379d](#)

Target Models: Click Build load and Run in required model for loading the target
[mcb_param_est_f28069_DRV8312](#)
[mcb_param_est_f28379D_DRV8305](#)

Test Status

Run Stop

Estimated Motor Parameters

Rs	0.4775	ohm
Ld	2.1052e-04	H
Lq	2.0117e-04	H
Bemf	--	Vpp/rpm
Motor Inertia	--	kg.m ²
Friction constant	--	N.m.s

Save Parameters Open Model

Signal Conditioning and Scaling

Algorithm

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Running 95%

Fault Status

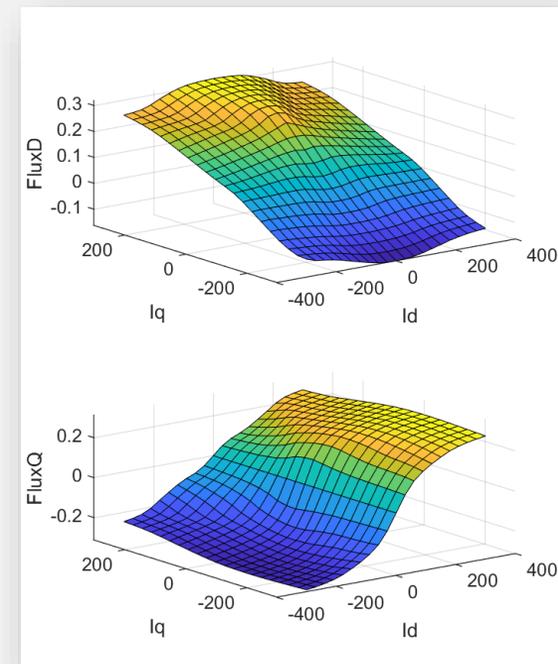
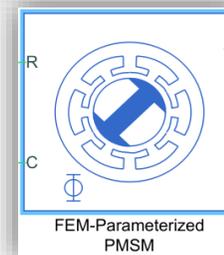
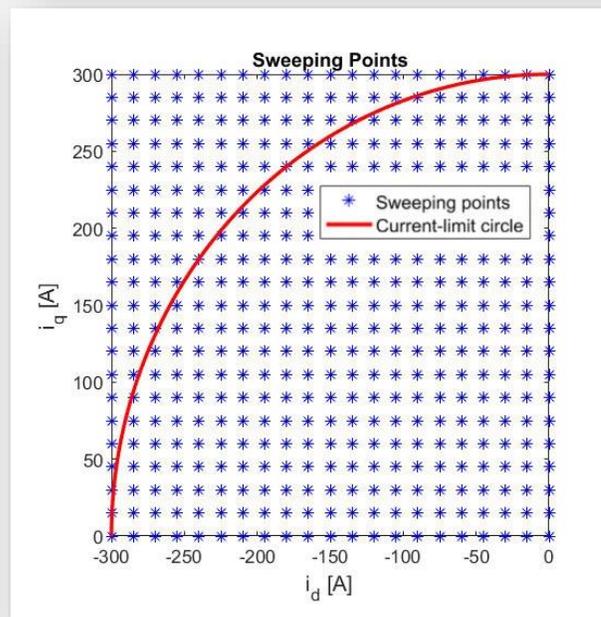
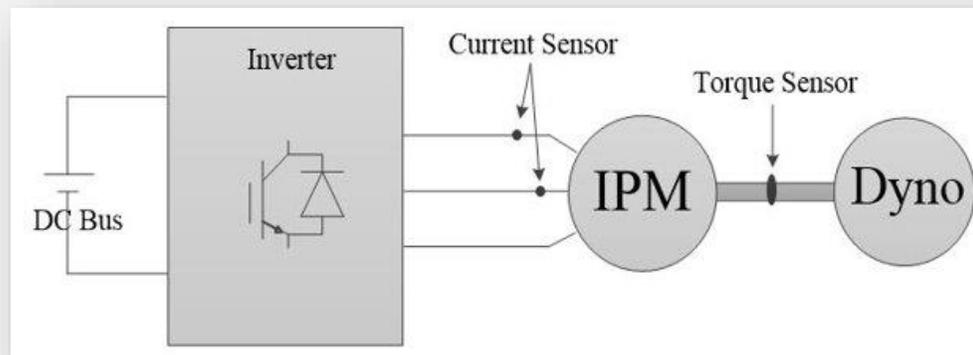
- Over Current
- Under Voltage
- Serial communication

Signal from Target

电机参数化和被控对象建模

- 选择电机类型和规格
- 电机参数化
- 被控对象建模

基于测功机试验获得Flux-I曲面



Block Parameters: FEM-Parameterized PMSM

FEM-Parameterized PMSM (DQ0 flux data)

This block implements the electrical and mechanical characteristics of a permanent magnet synchronous motor for which magnetic flux linkage depends nonlinearly on currents and rotor angle. Right-click on the block and select Simscape block choices to access variant implementations.

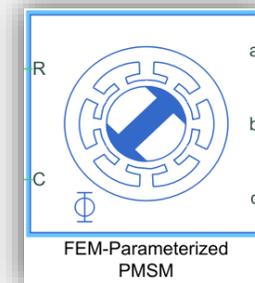
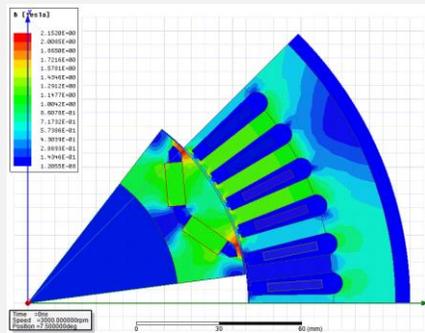
Settings

Electrical	Iron Losses	Mechanical	Variables
Flux linkage data format: D and Q axes flux linkages as a function of D-axis current (iD), Q-axis current (iQ), and rotor angle (theta)			
Winding type: Wye-wound			
Expose neutral port: No			
Number of pole pairs: N			
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
Quadrature-axis current vector, iQ:		iqVec	A
Rotor angle vector, theta:		angleVec	deg
D-axis flux linkage, Fd(iD,iQ,theta):		fluxD	Wb
Q-axis flux linkage, Fq(iD,iQ,theta):		fluxQ	Wb
Torque matrix, T(iD,iQ,theta):		torque	N*m
Interpolation method: Linear			
Stator resistance per phase, Rs: 0.07 Ohm			

电机参数化和被控对象建模

来自FEA电机设计工具

- 选择电机类型和规格
- 电机参数化
- 被控对象建模

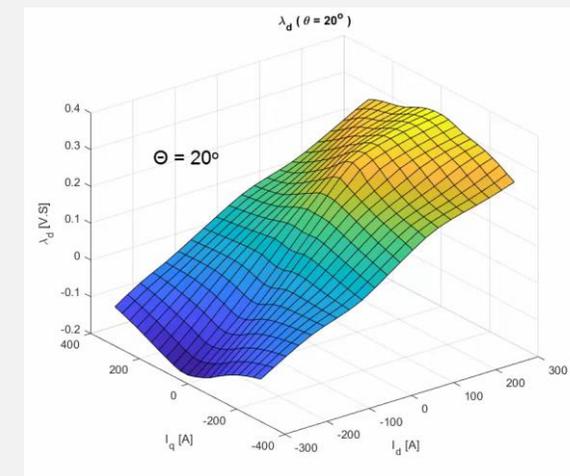


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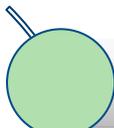
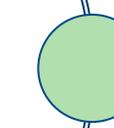
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* ANSYS and all other ANSYS, Inc. product names
* of ANSYS, Inc. or its subsidiaries in the United
* States is reproduced with permission of ANSYS, Inc.
*****
B_BasicData
  Version 1.0
  Poles 8
E_BasicData
B_PhaseImp 3
  PhaseA 1.0000000000e-003 1.0000000000e-003
  PhaseB 1.0000000000e-003 1.0000000000e-003
  PhaseC 1.0000000000e-003 1.0000000000e-003
E_PhaseImp
B_Sweepings
  Id_Iq (21: -300 -270 -240 -210 -180 -150 -120
        (21: -300 -270 -240 -210 -180 -150 -120
  Rotate (31: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
E_Sweepings
B_OutputMatrix DQ0
  
```

```

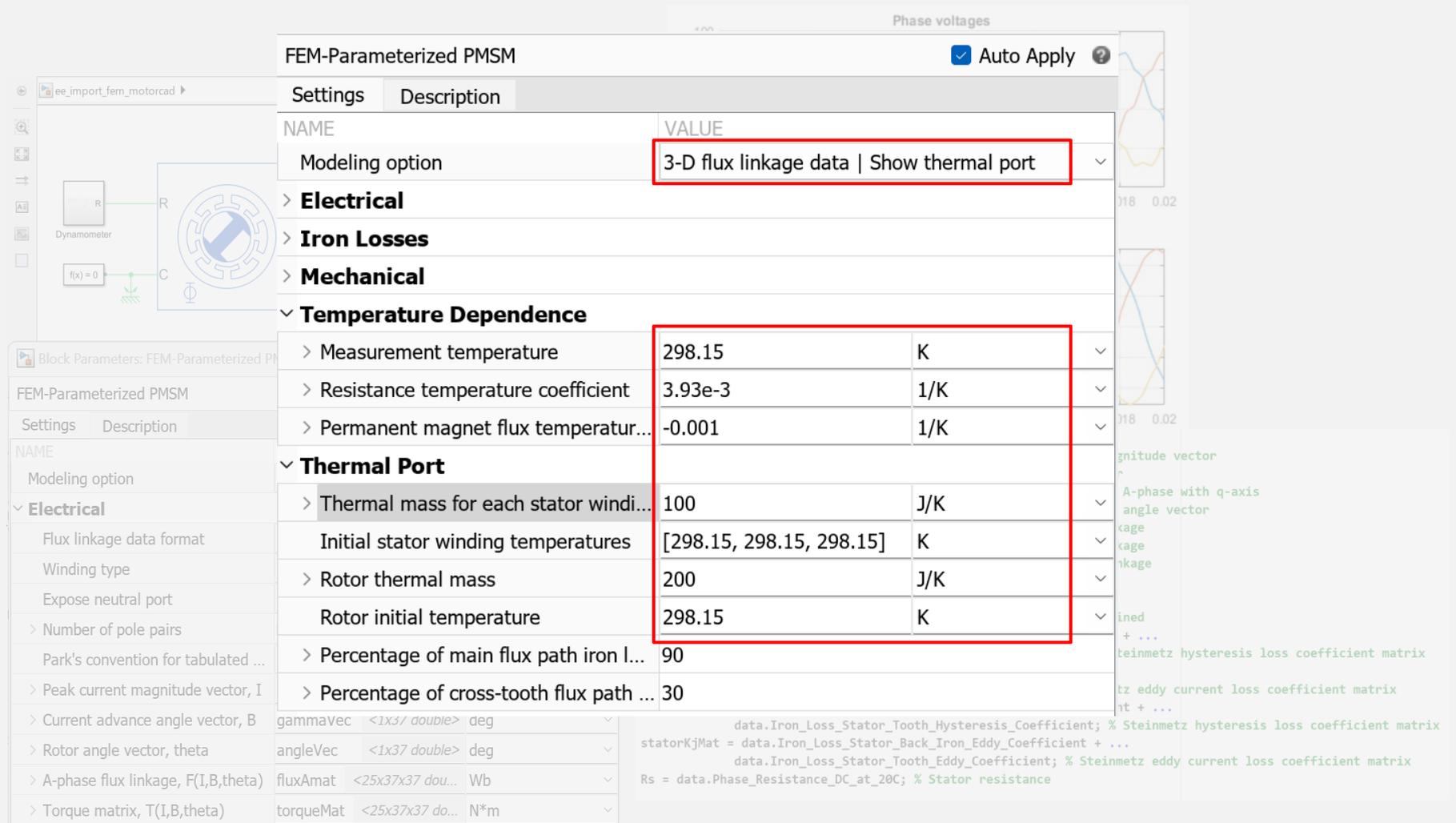
Editor - C:\Program Files\MATLAB\R2021a\toolbox\physmod\elec\eedemos\ee_ece_table.m
ee_ece_table.m x +
13
14 N = 8/2; % Number of pole pairs
15
16 %B_PhaseImp 3
17 % PhaseA 1.0000000000e-003 1.0000000000e-003
18 % PhaseB 1.0000000000e-003 1.0000000000e-003
19 % PhaseC 1.0000000000e-003 1.0000000000e-003
20 %E_PhaseImp
21
22 %B_Sweepings
23 idVec = [-300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 210 240 270 300];
24 iqVec = [-300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 210 240 270 300];
25 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 26 27 28 29 30 31];
26 %E_Sweepings
27
28 %B_OutputMatrix DQ0
29 data = [
30 % index fluxD
31 0 -9.2992778243e-002 -3.02
  
```



电机参数化和被控对象建模

-  选择电机类型和规格
-  电机参数化
-  被控对象建模

来自FEA电机设计工具



FEM-Parameterized PMSM Auto Apply

NAME	VALUE
Modeling option	3-D flux linkage data Show thermal port
Electrical	
Iron Losses	
Mechanical	
Temperature Dependence	
> Measurement temperature	298.15 K
> Resistance temperature coefficient	3.93e-3 1/K
> Permanent magnet flux temperatur...	-0.001 1/K
Thermal Port	
> Thermal mass for each stator windi...	100 J/K
> Initial stator winding temperatures	[298.15, 298.15, 298.15] K
> Rotor thermal mass	200 J/K
> Rotor initial temperature	298.15 K
> Percentage of main flux path iron l...	90
> Percentage of cross-tooth flux path ...	30

```

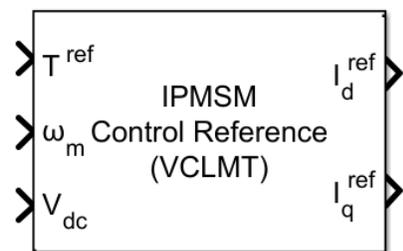
data.Iron_Loss_Stator_Tooth_Hysteresis_Coefficient; % Steinmetz hysteresis loss coefficient matrix
statorKjMat = data.Iron_Loss_Stator_Back_Iron_Eddy_Coefficient + ...
data.Iron_Loss_Stator_Tooth_Eddy_Coefficient; % Steinmetz eddy current loss coefficient matrix
Rs = data.Phase_Resistance_DC_at_20C; % Stator resistance
    
```

电机约束曲线和外特性

■ 绘制电机约束曲线

- MTPA 曲线 (最大转矩电流比)
- MTPV 曲线(最大转矩电压比)
- 电压约束
- 电流约束

■ 电机特性



LUT based PMSM Control Reference

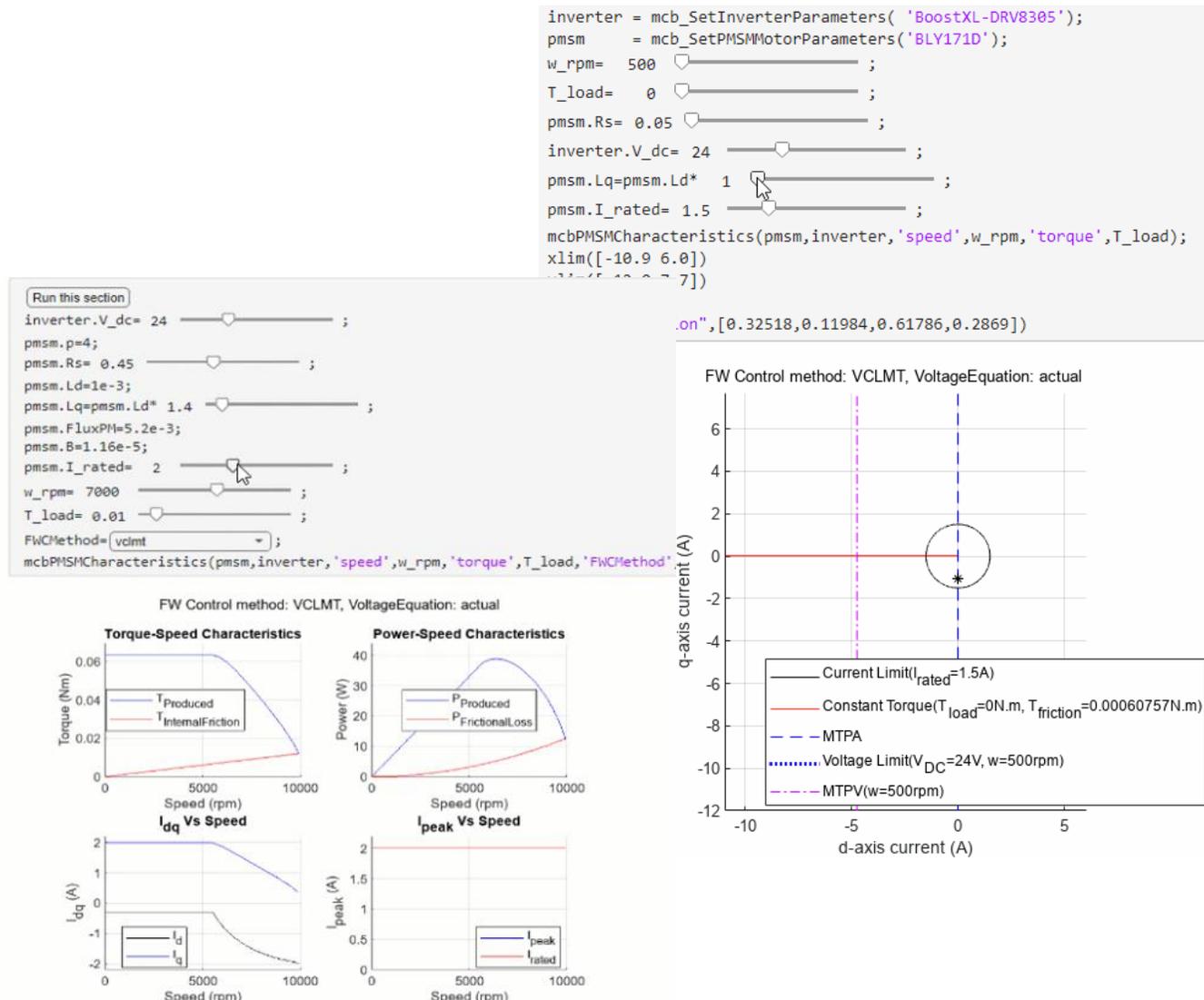
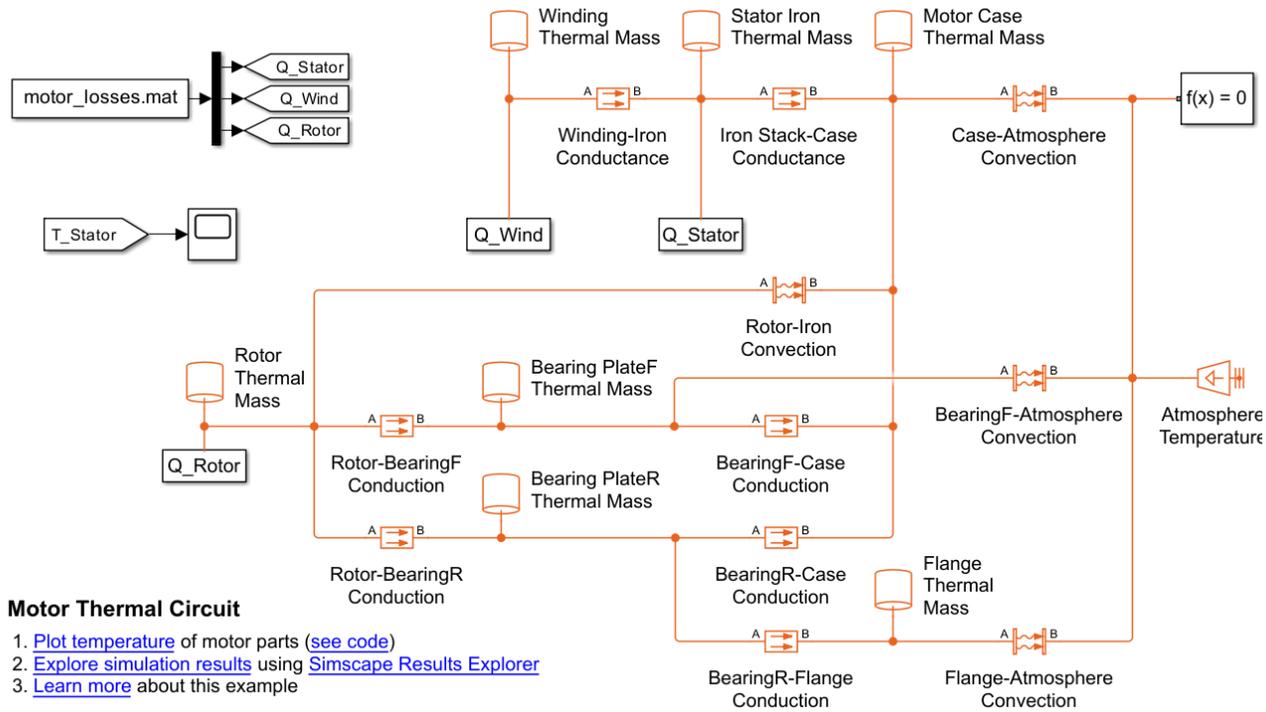


Figure : Dependency of curves and characteristics on parameters changes

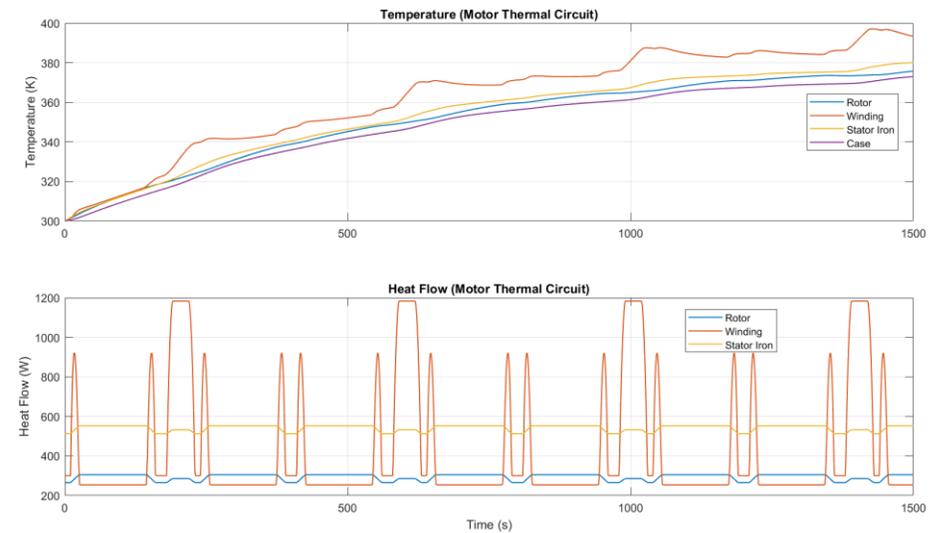
电机热路模型



Motor Thermal Circuit

1. [Plot temperature](#) of motor parts (see code)
2. [Explore simulation results](#) using [Simscape Results Explorer](#)
3. [Learn more](#) about this example

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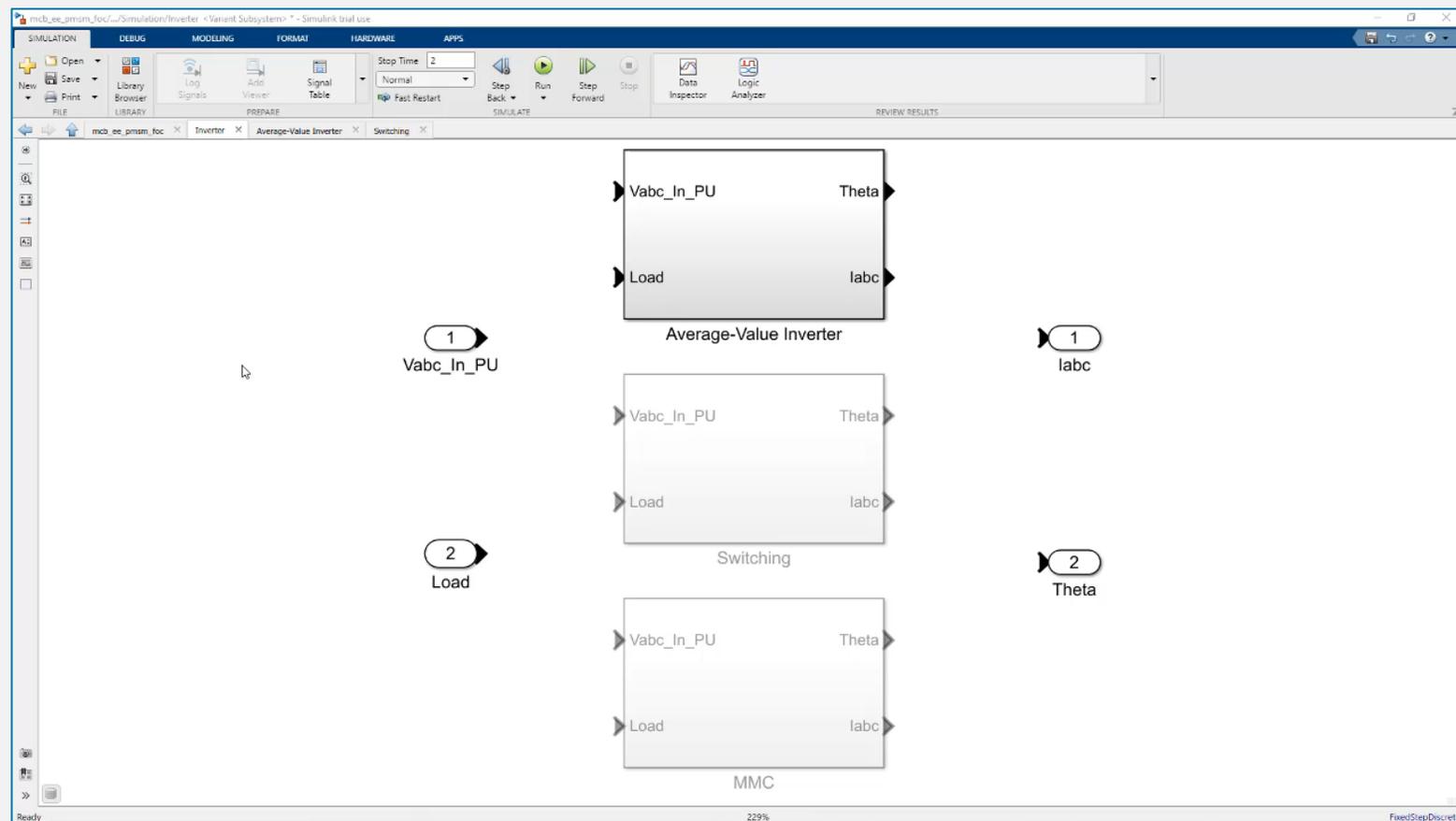
电机参数化和被控对象建模

不同电力电子保真度的变体模型

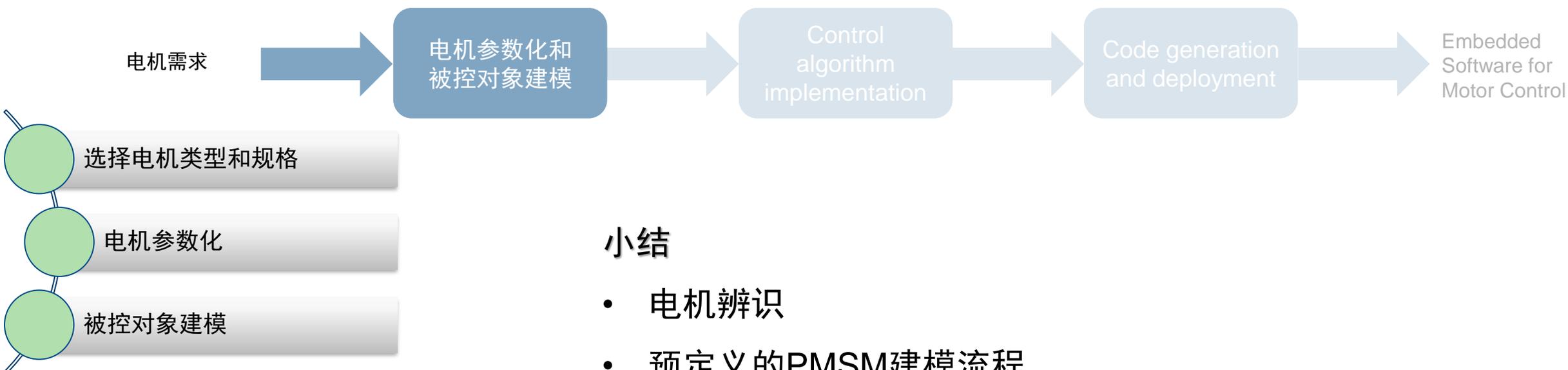
选择电机类型和规格

电机参数化

被控对象建模



电机参数化和被控对象建模



小结

- 电机辨识
- 预定义的PMSM建模流程
- 使用电机规格书、实验测试、FEA工具或测功机数据对电机进行参数化
- 对具有不同保真度的电机和逆变器进行建模

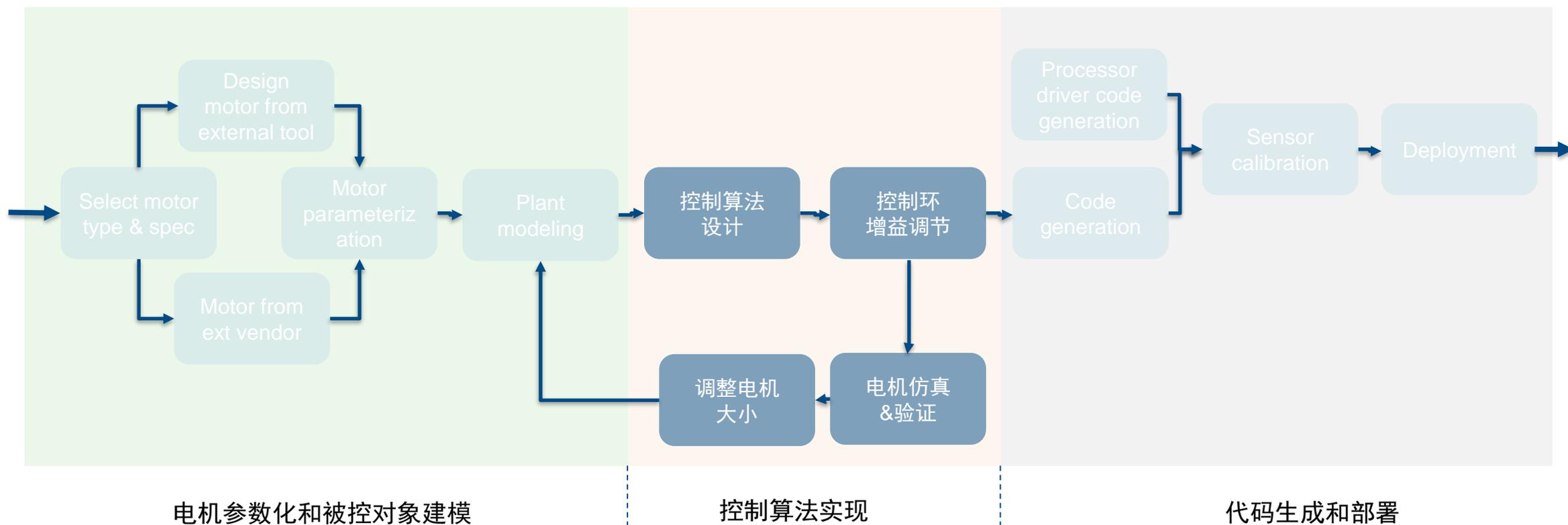


建模工程师

如何获取电机参数来开发电机模型？

使用电机测试、测功机测试或有FEA数据确定电机参数

建议的电动车驱动电机控制软件开发流程



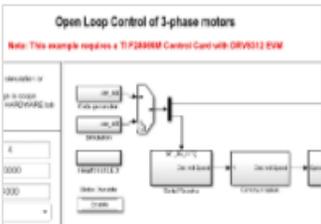
常见电机控制算法

控制算法设计

控制环增益调节

电机仿真&验证

调整电机大小



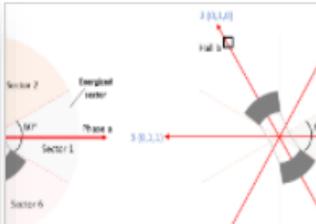
Open Loop Control of 3-phase motors
 Note: This example requires a T1F2800M Control Card with DRV8321 EVM

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Run 3-Phase AC Motors in Open-Loop Control and Calibrate ADC Offset

Uses open-loop control (also known as scalar control or Volts/Hz control) to run a motor. This technique varies the stator voltage

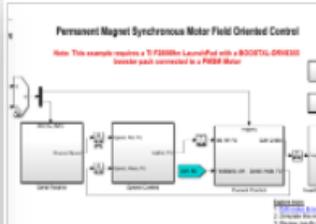
V/F控制



Six-Step Commutation of BLDC Motor Using Sensor Feedback

Uses 120-degree conduction mode to implement the six-step commutation technique to control the speed and direction of rotation of a

BLDC六步换相



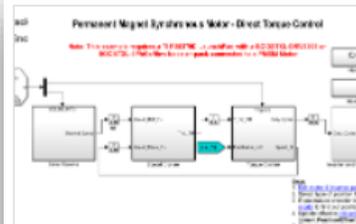
Permanent Magnet Synchronous Motor Field Oriented Control
 Note: This example requires a T1F2800M Control Card with a BOOSTXL-DRIVE1000 board pack connected to a PMSM Motor

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Sensorless Field-Oriented Control of PMSM

Implements the field-oriented control (FOC) technique to control the speed of a three-phase permanent magnet synchronous

磁场定向控制



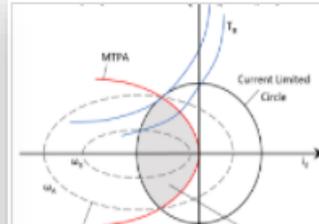
Permanent Magnet Synchronous Motor - Direct Torque Control
 Note: This example requires a T1F2800M Control Card with a BOOSTXL-DRIVE1000 board pack connected to a PMSM Motor

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Direct Torque Control of PMSM Using Quadrature Encoder or Sensorless Flux...

Implements direct torque control (DTC) technique to control the speed of a three-phase permanent magnet synchronous motor (PMSM). Direct

直接转矩控制



Field-Weakening Control (with MTPA) of PMSM

Implements the field-oriented control (FOC) technique to control the torque and speed of a three-phase permanent magnet

弱磁控制

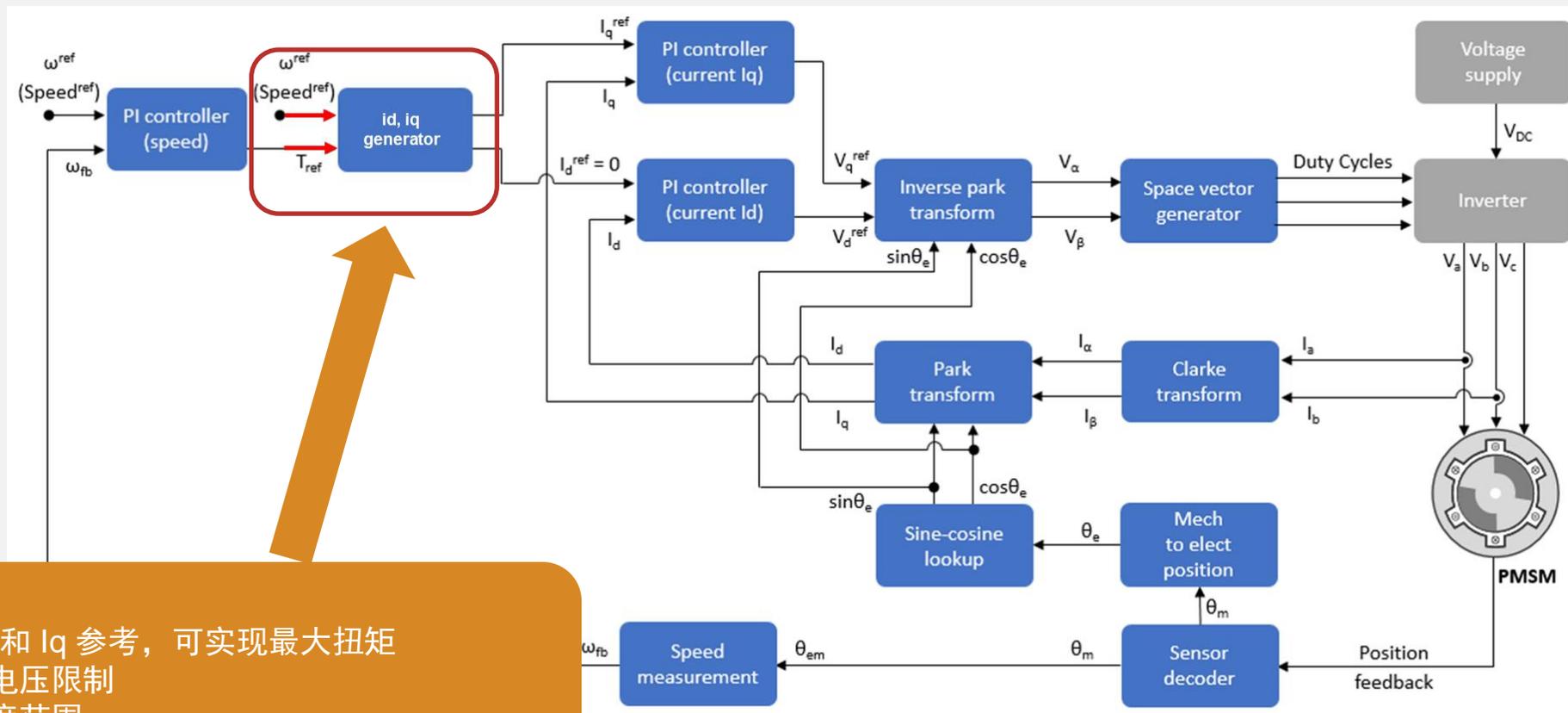
弱磁控制模块

控制算法设计

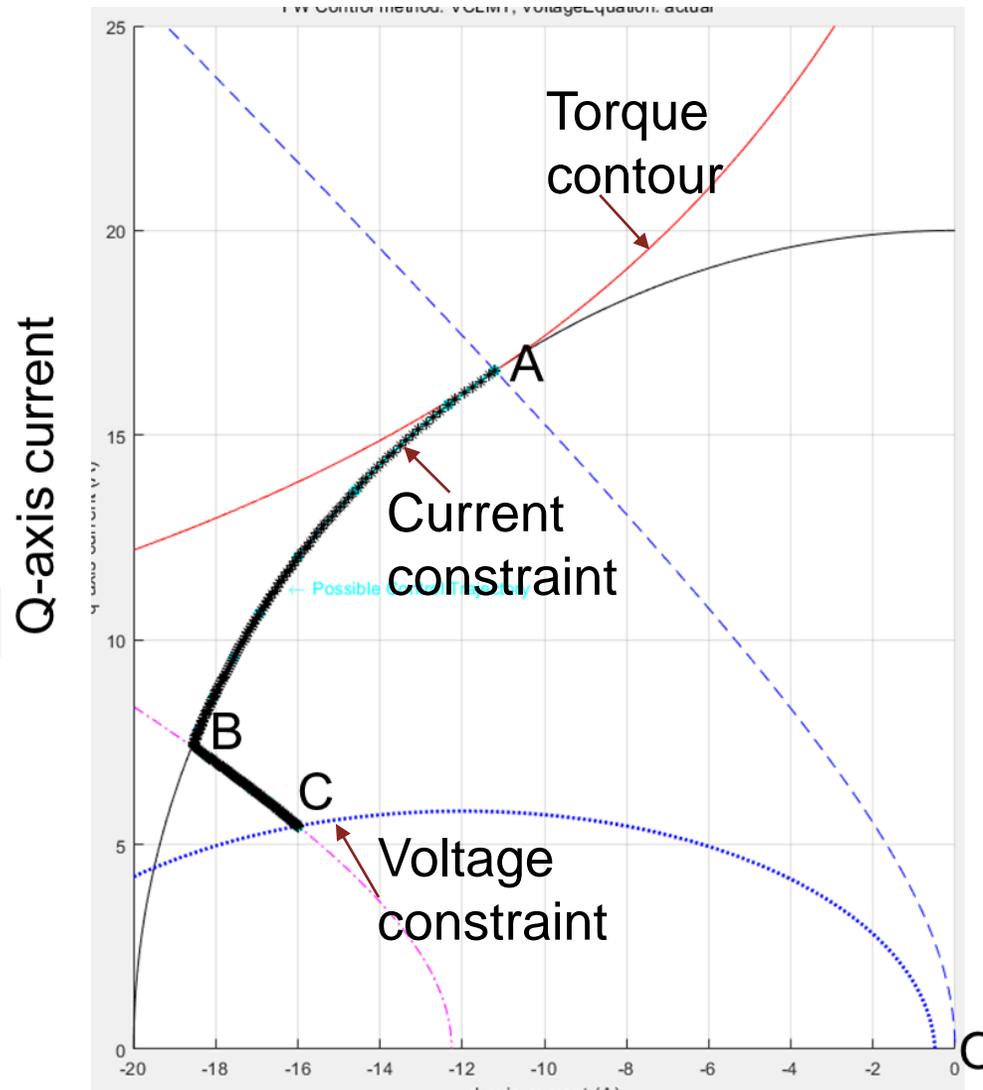
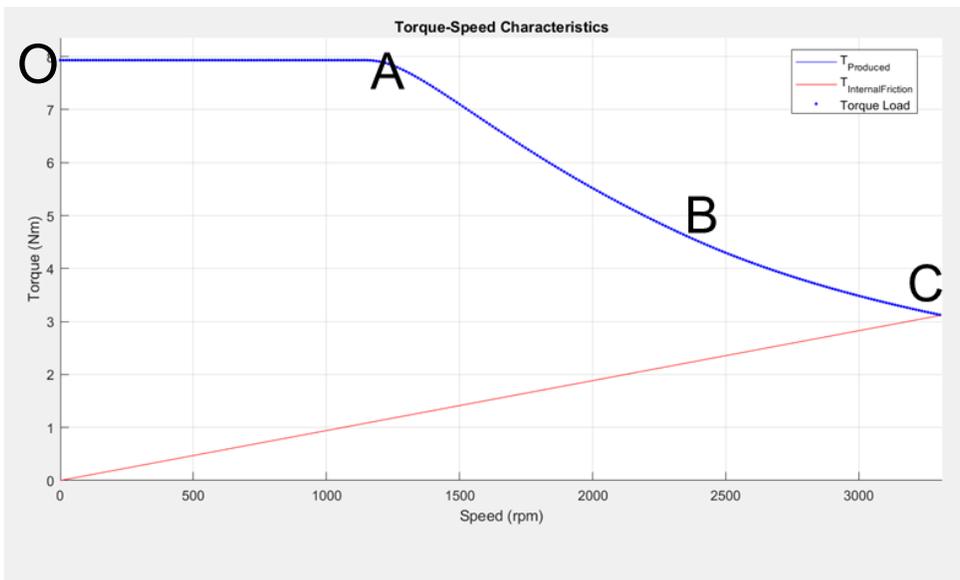
控制环增益调节

电机仿真&验证

调整电机大小



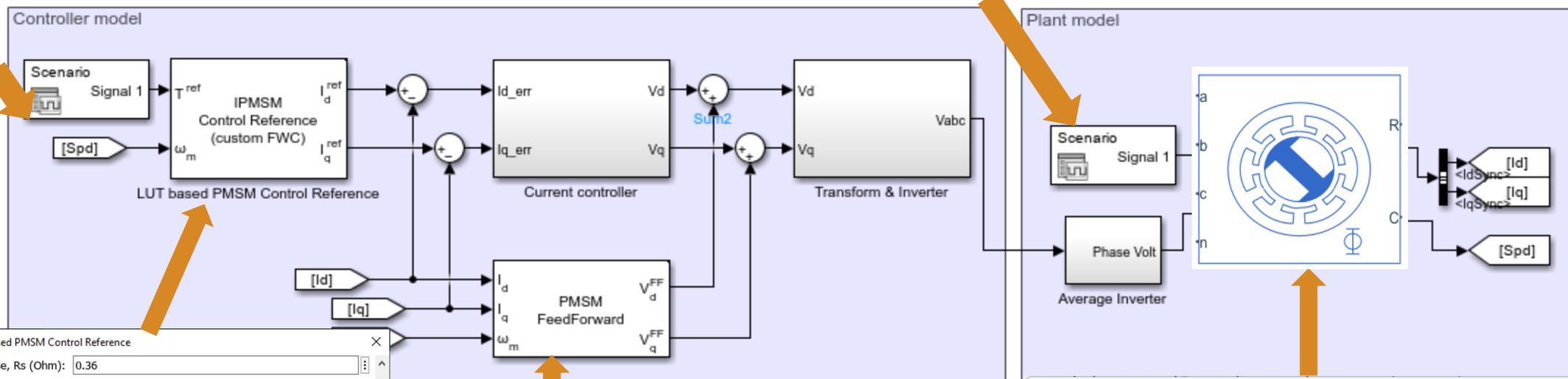
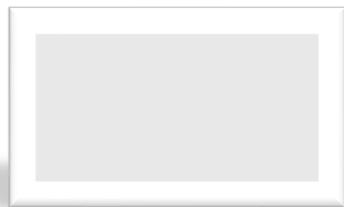
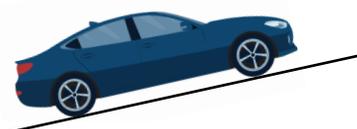
比较转矩-速度特性曲线和Id/Iq图谱中的关键运行点。



Region	Algorithm / Constraints
OA	MTPA运行区域
AB	弱磁运行区 (满足电流约束)
BC	MTPV运行区域
CO	弱磁运行区 (满足电压约束)
C	C 是最大运行速度 (此时电机驱动扭矩与摩擦力矩相等)

D-axis current

使用电机测功机数据实现弱磁控制



Block Parameters: LUT based PMSM Control Reference

Stator resistance per phase, Rs (Ohm): 0.36

Motor parameter input method: Non-linear model with id and iq LUTs

Block Parameters: PMSM FeedForward Control

Number of pole pairs: 4

Motor parameter input method: Non-linear model with D,Q-flux linkage LUTs

Direct-axis current breakpoint vector, id (A): [-40, -20, 0, 20]

Quadrature-axis current breakpoint vector, iq (A): [-40, -20, 0, 20, 40]

Direct-axis flux linkage LUT, FluxD(id,iq) (Wb): [4;6.4,6.4,6.4,6.4,6.4;10.4,10.4,10.4,10.4,10.4]*1e-

Quadrature-axis flux linkage LUT, FluxQ(id,iq) (Wb): [-8,-4,0,4,8;-8,-4,0,4,8;-8,-4,0,4,8;-8,-4,0,4,8]*1e-

Input method: Mask input

Output voltage saturation (V): 24/sqrt(3)

Block Parameters: FEM-Parameterized PMSM

FEM-Parameterized PMSM

Settings: Auto Apply

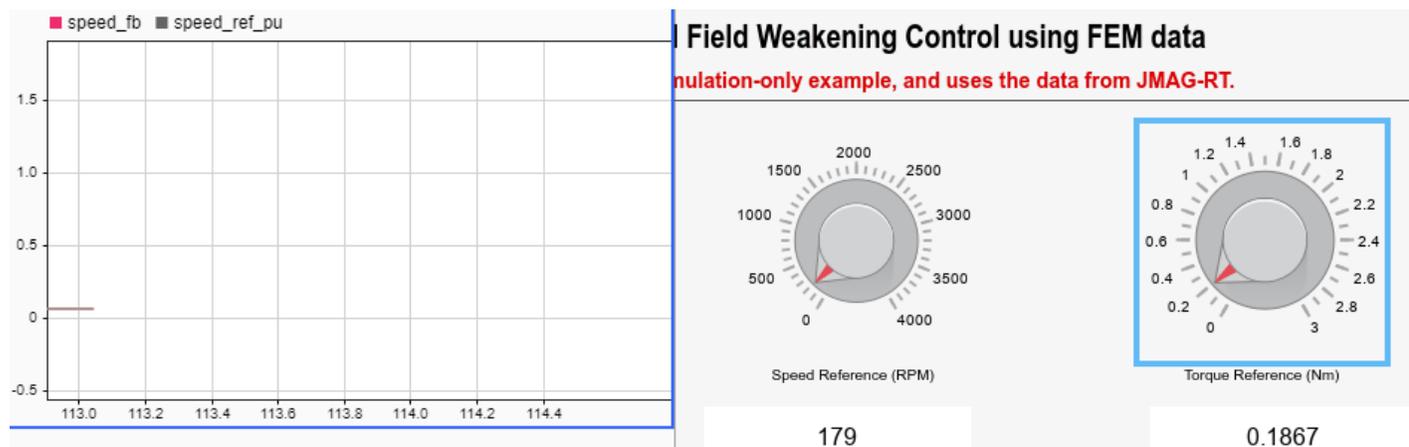
NAME	VALUE
Modeling option	2-D partial derivative data No thermal port
Electrical	
Parameterization	Assume sinusoidal back emf - tabulate with d- and q-axis currents
Winding type	Wye-wound
Direct-axis current vector, id	[-200, 0, 200] A
Quadrature-axis current vector, iq	[-200, 0, 200] A
Ld matrix, Ld(id,iq)	0.0002 * ones(3, 3) <3x3 double> H
Lq matrix, Lq(id,iq)	0.0002 * ones(3, 3) <3x3 double> H
Permanent magnet flux linkage, PM(id,iq)	0.1 * ones(3, 3) <3x3 double> Wb

EV电机控制工程师

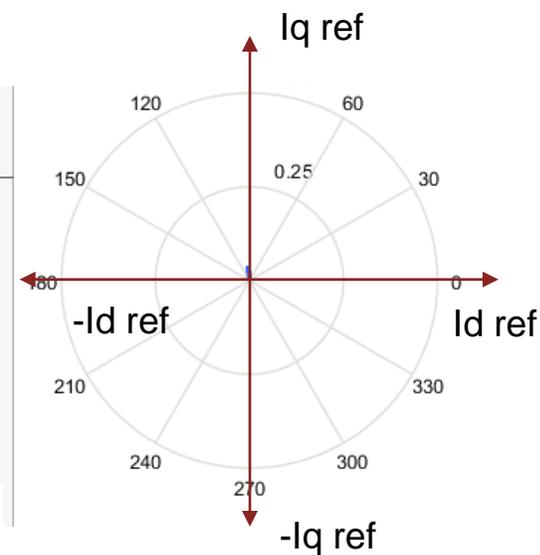
我应该遵循哪些步骤来实施有效的弱磁控制？
使用测功机测试数据按照以上工作流程实现弱磁控制

OK Cancel Help Apply

IPMSM的弱磁控制仿真



参考速度 vs. 实际速度（阶跃测试）



Id 和 Iq 图

IPMSM弱磁控制硬件测试结果

PMSM Field Weakening Control Host

HOST
Serial Setup

Note:
1. Update workspace with variables used in [target model](#)
2. Select the serial port in 'Host Serial Setup' (Blue Color)
3. Use 'Motor Start / Stop' switch to control motor.
4. Input speed request using 'Reference Speed' block.
5. Observe the debug signals in scope.



Start / Stop
Field Weakening Control



Start / Stop Motor

- Debug signals
- Speed_ref & Speed_feedback
 - Id_ref & Id_feedback
 - Iq_ref & Iq_feedback
 - Torque & Power
 - Ia & Ib



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Ready Frame based Offset=0 T=2.160

DroidCam

Base Speed = 6224 rpm
Current Speed = 0rpm



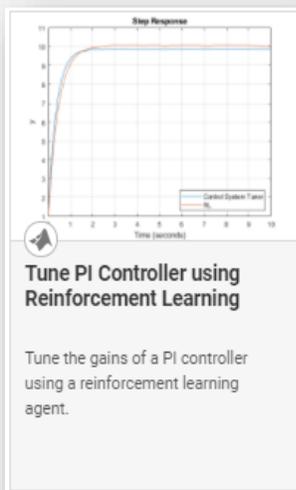
其它先进控制策略

控制算法设计

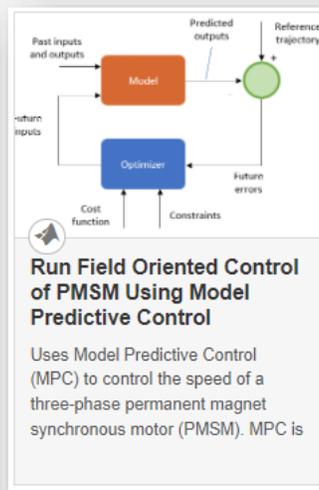
控制环增益调节

电机仿真&验证

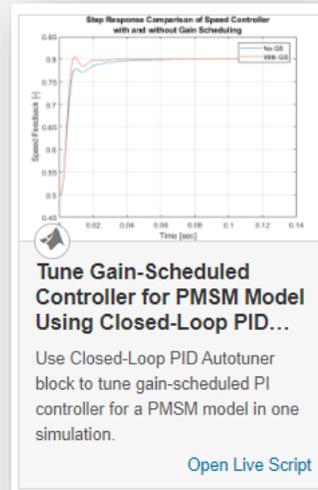
调整电机大小



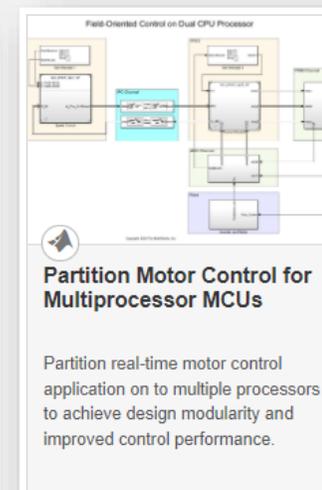
使用加强学习
进行PID调参



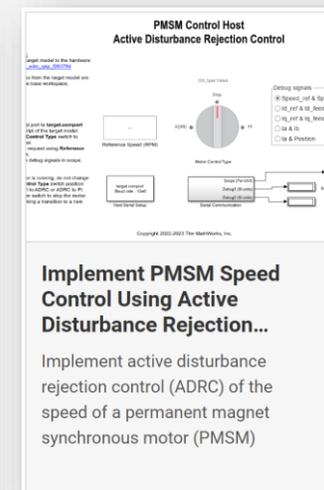
模型预测控制



增益调度控制



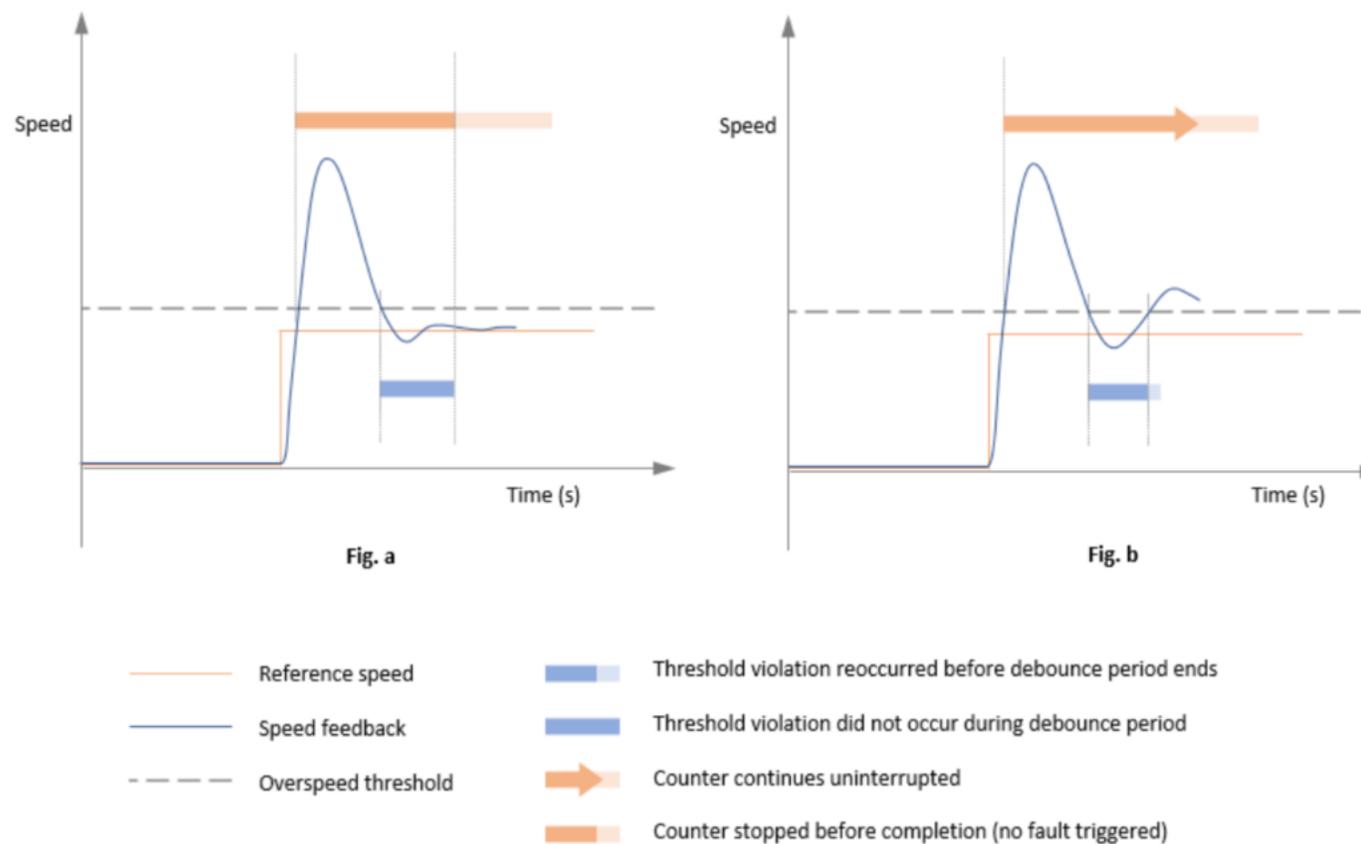
多处理器 MCU 的电
机控制仿真



自抗扰控制

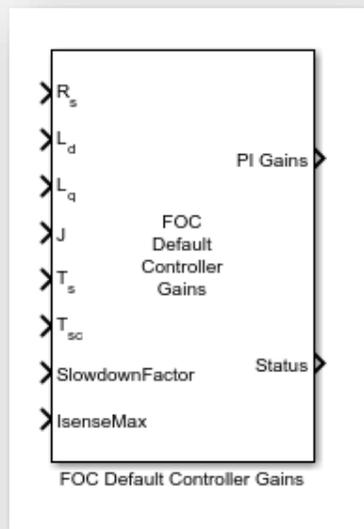
电机保护策略 - 继电器模块

- 过流保护
- 过压保护
- 欠压保护
- 超速保护



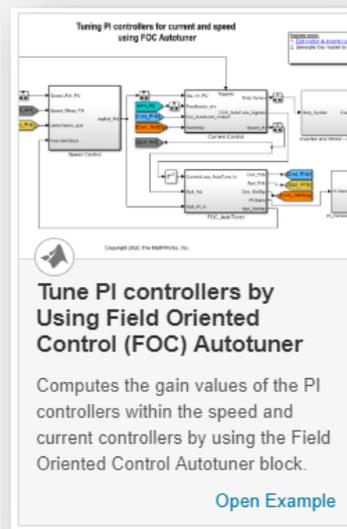
调整控制环增益

- 控制算法设计
- 控制环增益调节
- 电机仿真&验证
- 调整电机大小



经验值计算

Motor Control Blockset

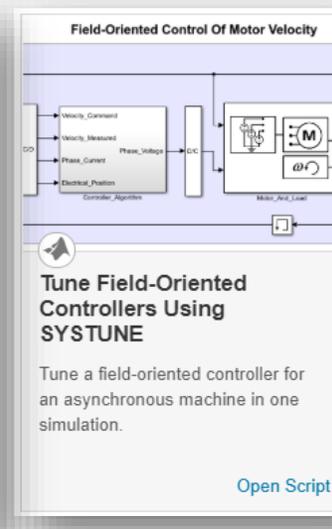


FOC Autotuner

Motor Control Blockset and Simulink Control Design



在线频谱估计 + PID tuner app

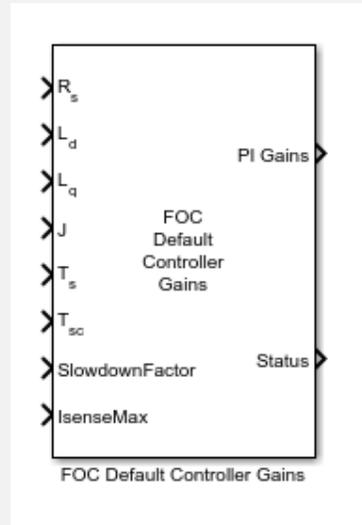


经典控制理论

Simulink Control Design

调整控制环增益

- 控制算法设计
- 控制环增益调节
- 电机仿真&验证
- 调整电机大小



Empirical Computation

Control Blockset

Tuning PI controllers for current and speed using FOC Autotuner

Tune PI controllers by Using Field Oriented Control (FOC) Autotuner

Computes the gain values of the PI controllers within the speed and current controllers by using the Field Oriented Control Autotuner block.

[Open Example](#)

FOC Autotuner

Motor Control Blockset and Simulink Control Design

PMSM Frequency Response Estimation Control Host

PID Tuner App with plant frequency response from hardware

Online frequency estimation and PID tuner app

Field-Oriented Control Of Motor Velocity

Tune Field-Oriented Controllers Using SYSTUNE

Tune a field-oriented controller for an asynchronous machine in one simulation.

[Open Script](#)

Classical Control Theory

Simulink Control Design

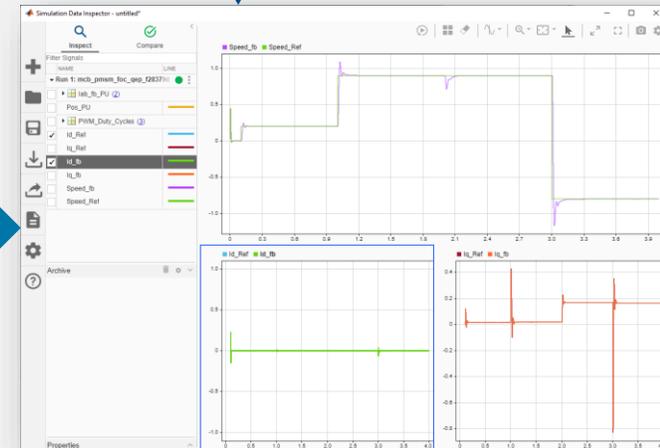
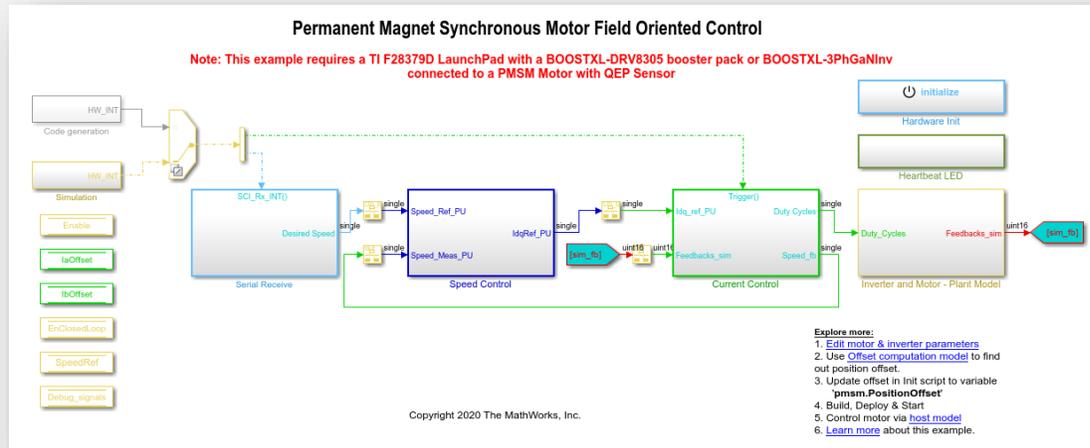
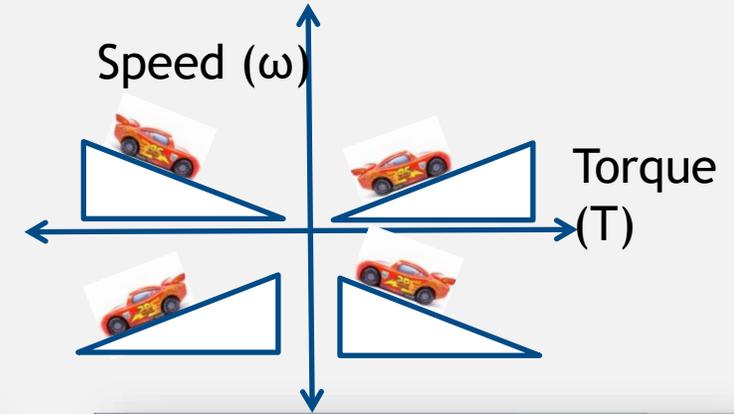
控制工程师

如何调整控制环路增益以实现性能?
使用本页列出的任何一种方法来调整控制增益

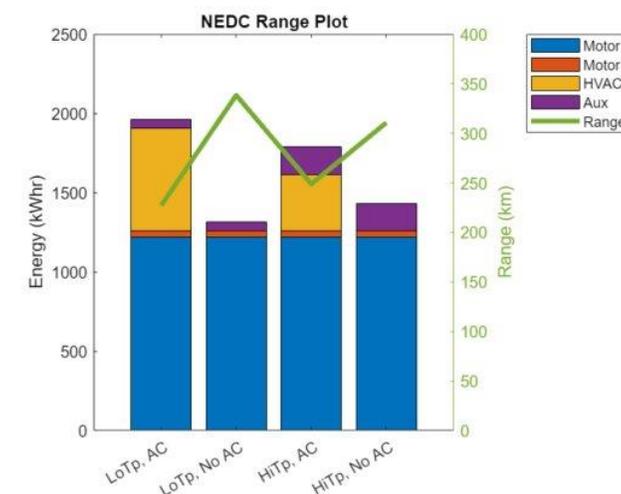
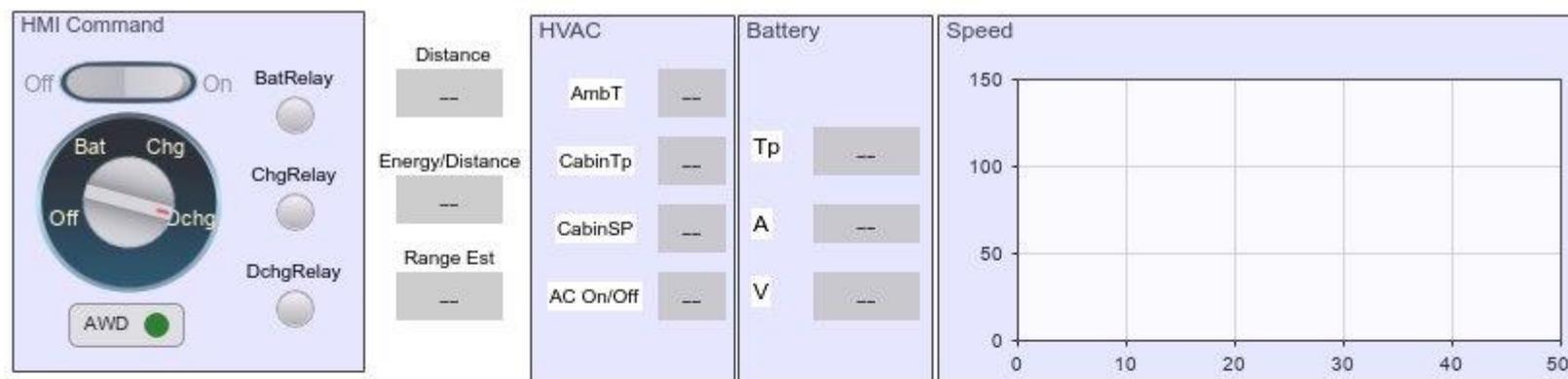
仿真验证

- 控制算法设计
- 控制环增益调节
- 电机仿真&验证
- 调整电机大小

仿真四象限运行并验证电机和控制特性

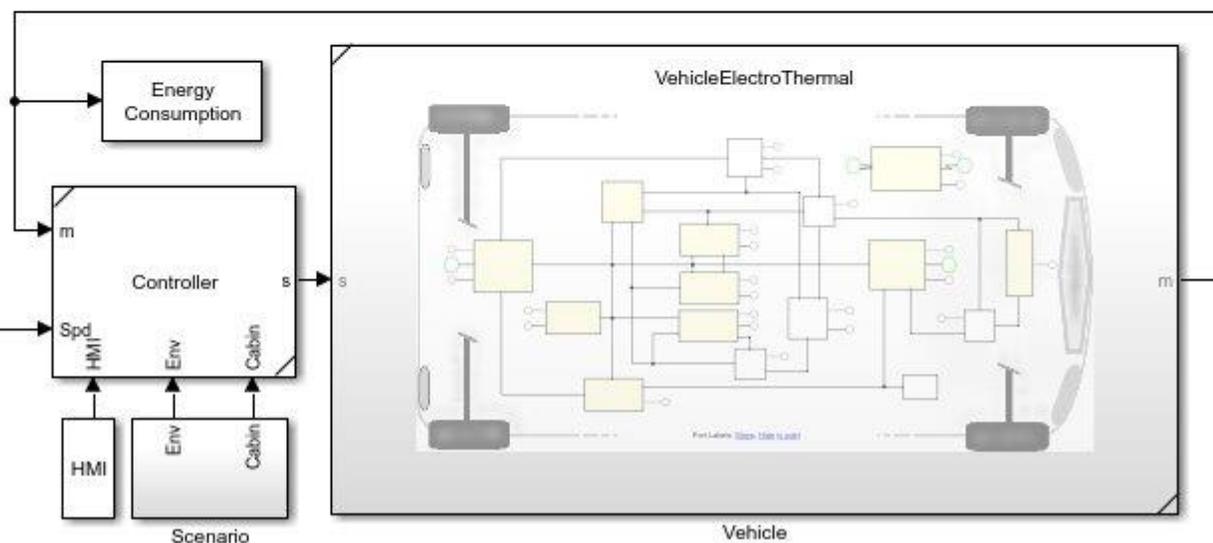
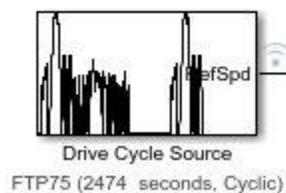


整车系统仿真



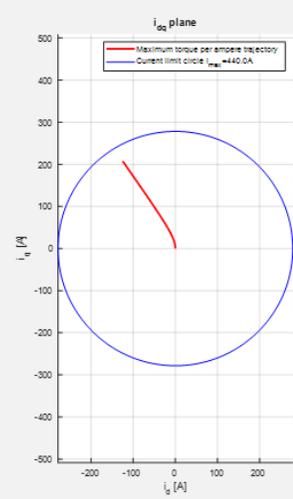
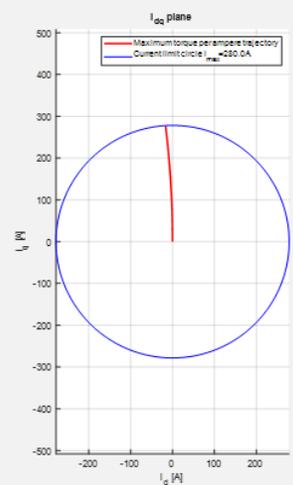
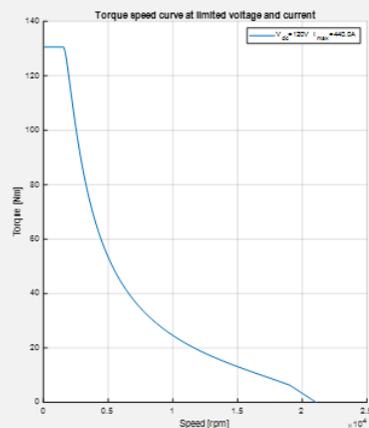
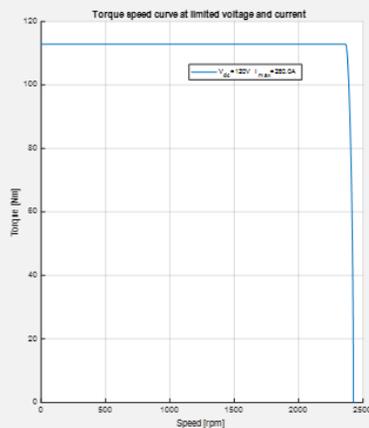
BEV Plant Model

1. Open project [page](#)
2. [Set parameters](#) for model
3. [Learn](#) more about this example
4. [Explore simulation results](#) using [Simscape Results Explorer](#)



根据系统要求重新设计电机

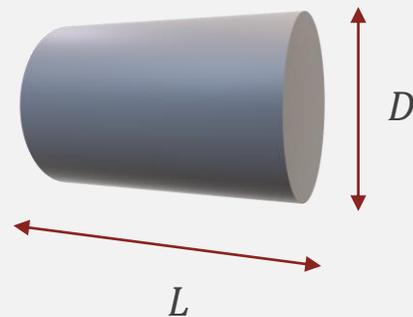
- 控制算法设计
- 控制环增益调节
- 电机仿真&验证
- 调整电机大小



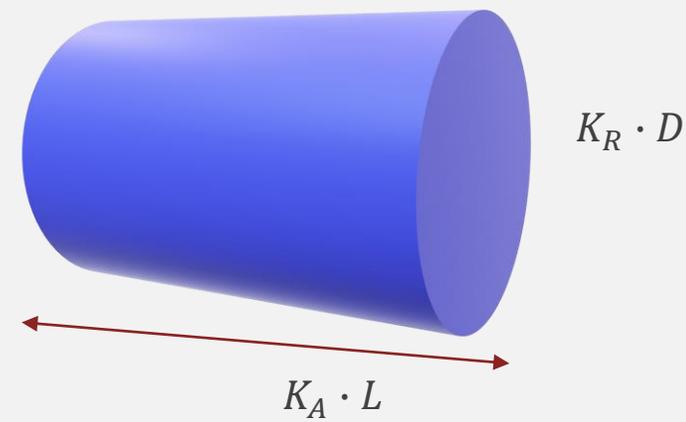
Existing characteristics

Proposed characteristics

Initial Design



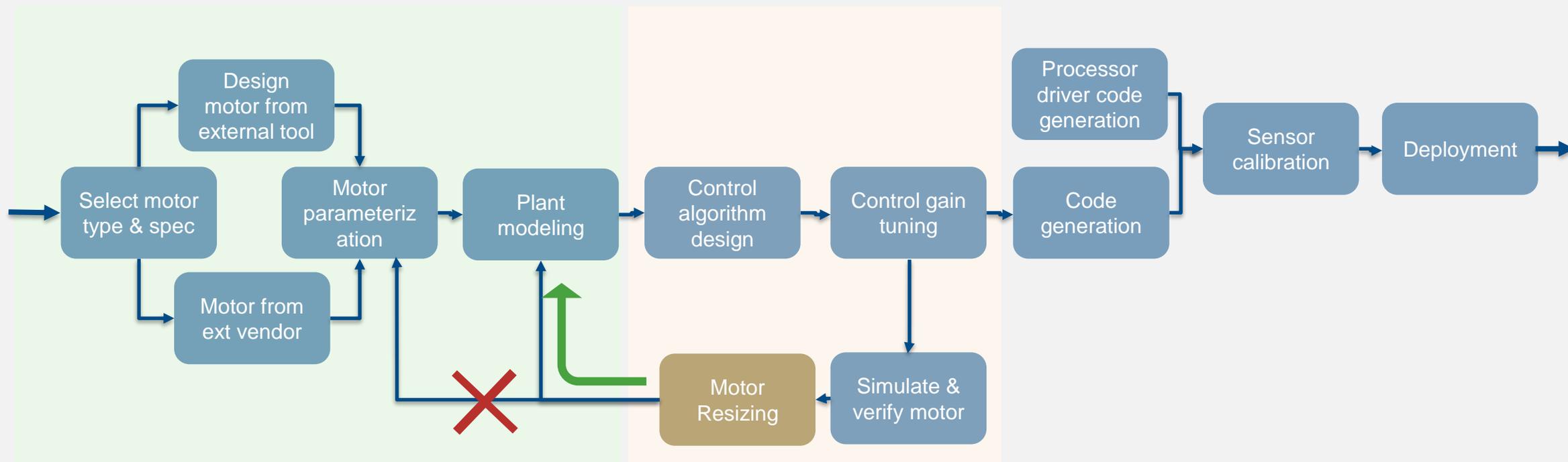
Resized Design



Where,

- K_A is the axial resize factor
- K_R is the radial resize factor
- K_W is the rewinding factor
- D is the diameter of motor
- L is the length of motor

无需重新参数化

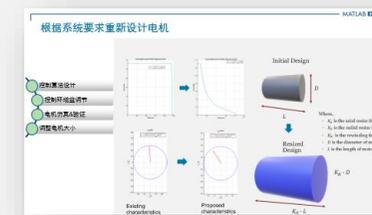


电机参数化和被控对象建模

控制算法实现

代码生成和部署

- 对于重新设计的电机无需再次运行测功机测试
- 重用已有的电机参数（乘以系数）
- 节省台架测试时间和费用



Motor Resizing

实现控制算法并在仿真中进行验证



控制算法设计

控制环增益调节

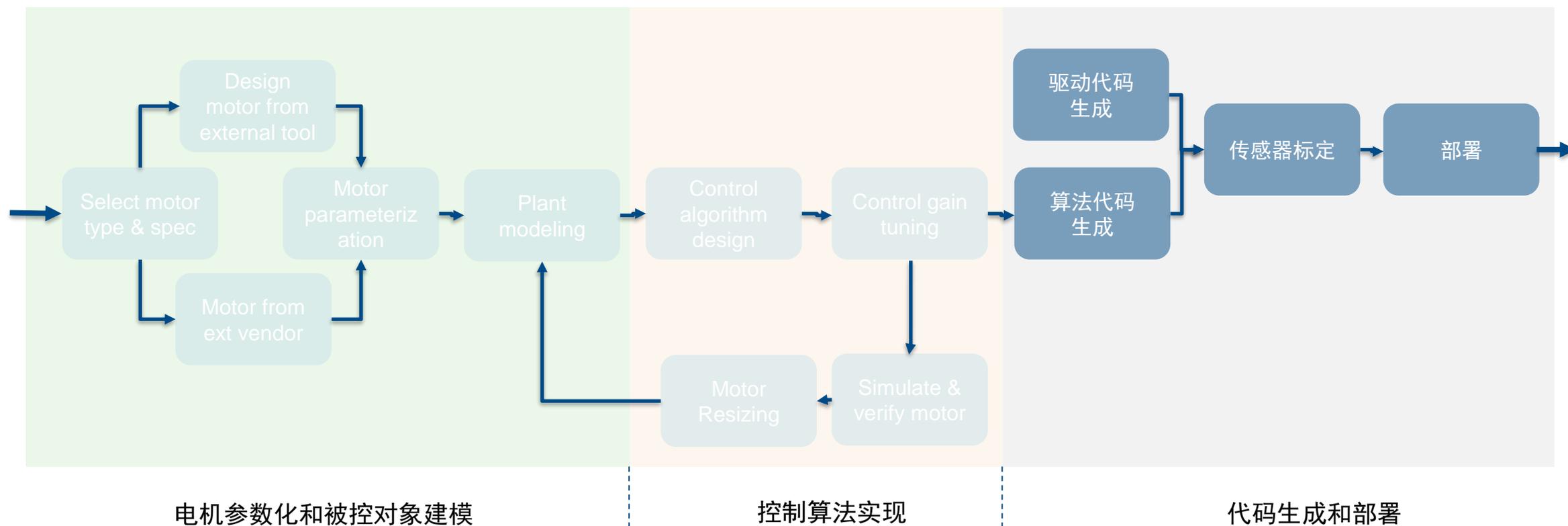
电机仿真&验证

调整电机大小

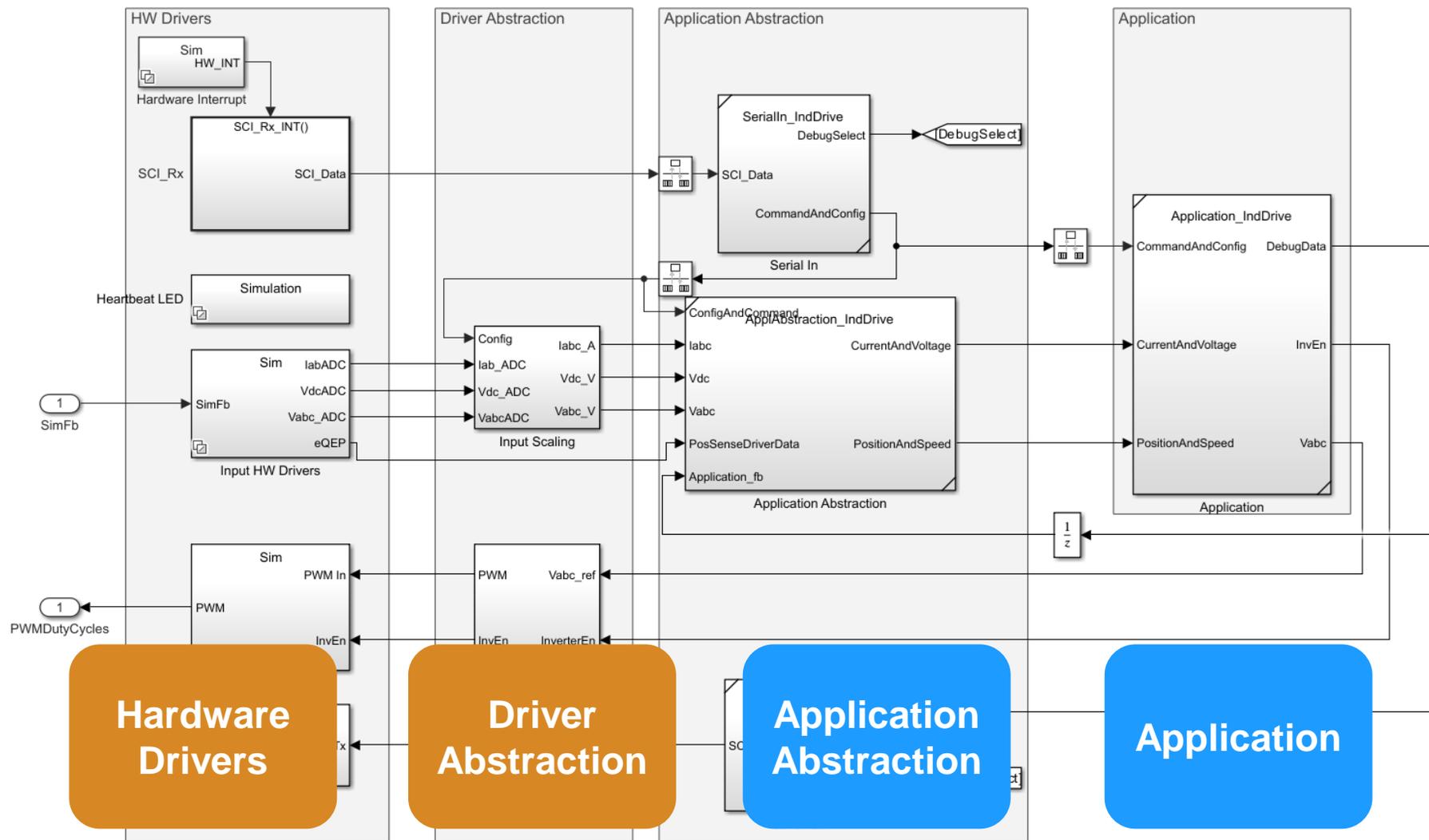
小结

- 了解常见的控制策略和新的控制策略
- 讨论弱磁控制(MTPA, MTPV)
- 讨论控制环增益调整的方法
- 讨论电机重新设计

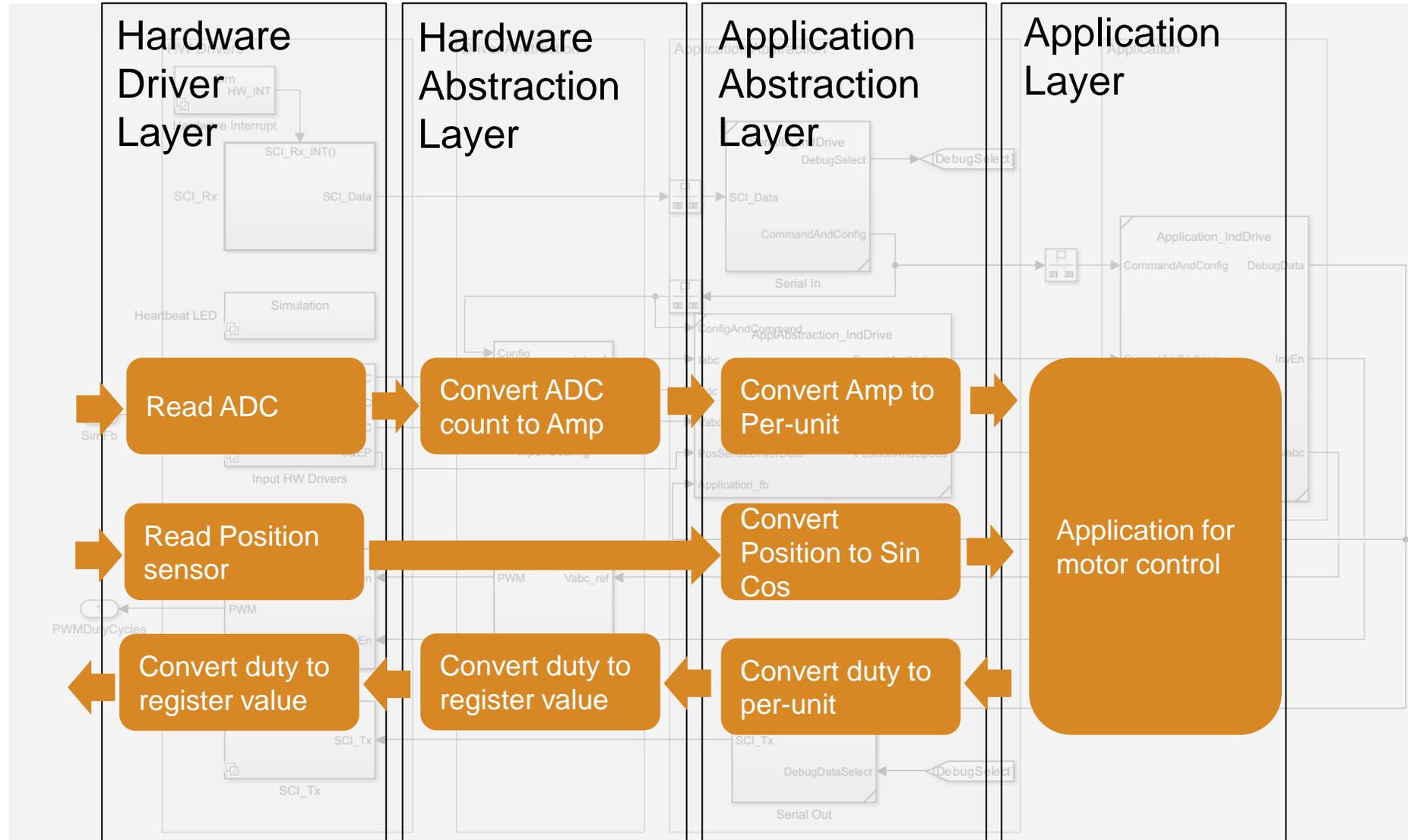
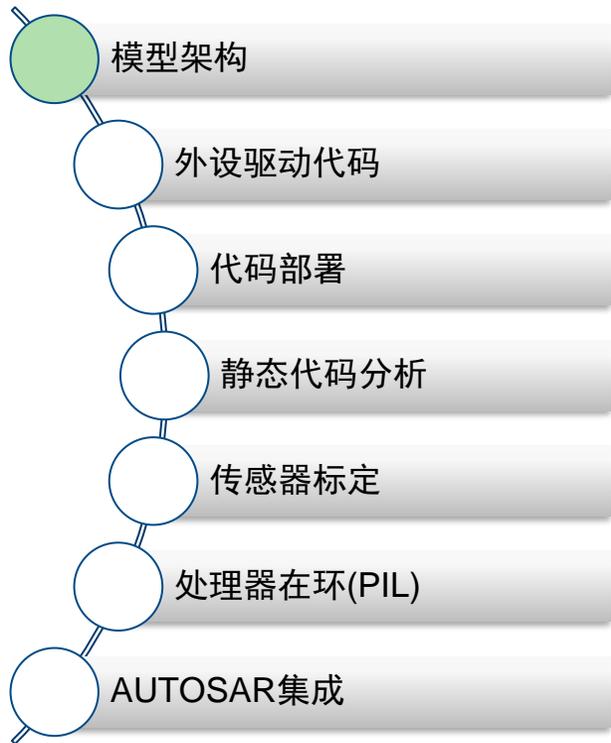
建议的电动车驱动电机控制软件开发流程



模型架构及层次——便于算法在不同硬件之间的移植（从原型到产品）



模型架构及层次——便于算法在不同硬件之间的移植（从原型到产品）



硬件驱动代码——来自硬件支持包或驱动模块

ADC, PWM, Interrupt trigger, Serial communication blocks

模型架构

外设驱动代码

代码部署

静态代码分析

传感器标定

处理器在环(PIL)

AUTOSAR集成

Simulink Library Browser

instrument control

C2000 Microcontroller Blockset/F2837xD

- C2806x
- C280x
- C281x
- C2833x
- C2834x
- F280013x
- F280015x
- F28002x
- F28003x
- F28004x
- F2807x
- F2837xD
- F2837xS
- F2838x
- F28M35x
- F28M36x
- F28p65x
- Host Communicatio
- Memory Operatio
- Optimization
- Scheduling
- Sensors
- Target Communic
- Test Bench Blocks
- > Communications Tool
- > Communications Tool
- > Communications Tool
- > Computer Vision Tool

ADC, CAN RCV, CAN XMT, CLAMath, CLA Subsystem, CLATaskTrigger, CMPSS1H, DAC-A, Digital Input, Digital Output, eCAP, ePWM1, eQEP, I2C RCV, I2C XMT, IPC Receive, IPC Transmit, SCI RCV, SCI XMT, SDFM-1, SDFM, PIEIFR12.INT8, SPI Controller Transfer, SPI Receive, SPI Transmit, Watchdog

Block Parameters: ADC

ADC Type 3-5 (mask) (link)

Configures the Type 3 to Type 5 ADC to output data collected from the ADC pins on the processor.
SOC: Start of Conversion
EOC: End of Conversion

SOC Trigger Input Channels

ADC Module A

ADC Resolution 12-bit (Single-ended input)

SOC trigger number SOC0

SOCx acquisition window 15

SOCx trigger source Software

ADCINT will trigger SOCx No ADCINT

Sample time: 0.001

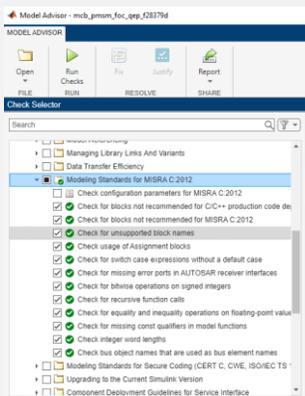
Data type: uint16

Post interrupt at EOC trigger

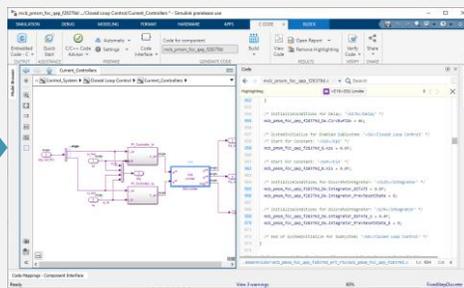
OK Cancel Help Apply

生成C代码或HDL代码，并与外设驱动代码集成

- 模型架构
- 外设驱动代码
- 代码部署
- 静态代码分析
- 传感器标定
- 处理器在环(PIL)
- AUTOSAR集成

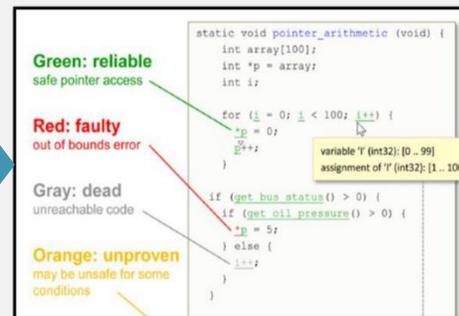


运行建模规范检查并符合Misra-C 和 ISO26262

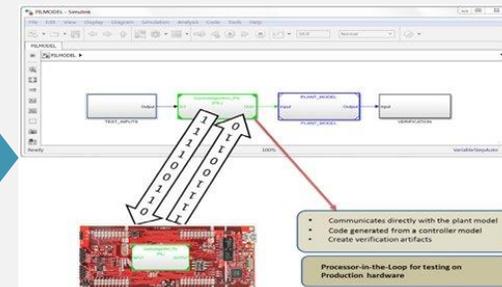


使用Embedded Coder生成代码

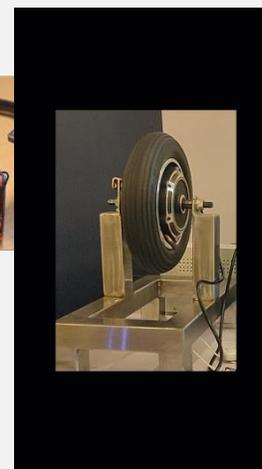
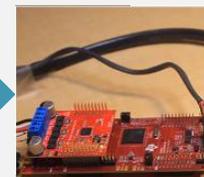
外设驱动代码 (手写代码或者通过硬件支持包自动生成)



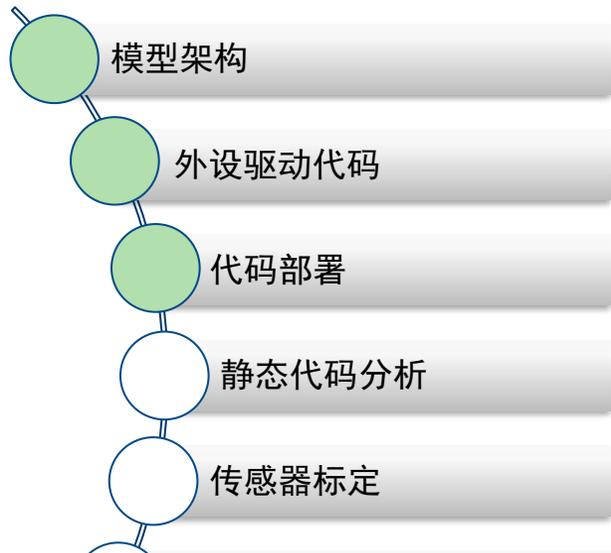
使用Polyspace运行静态代码分析



处理器在环测试 (验证代码执行时间)



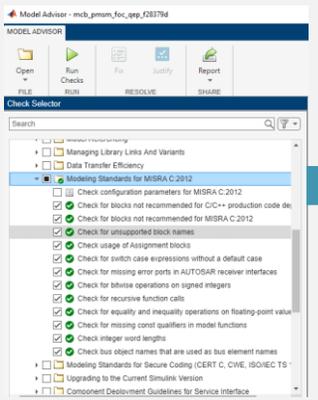
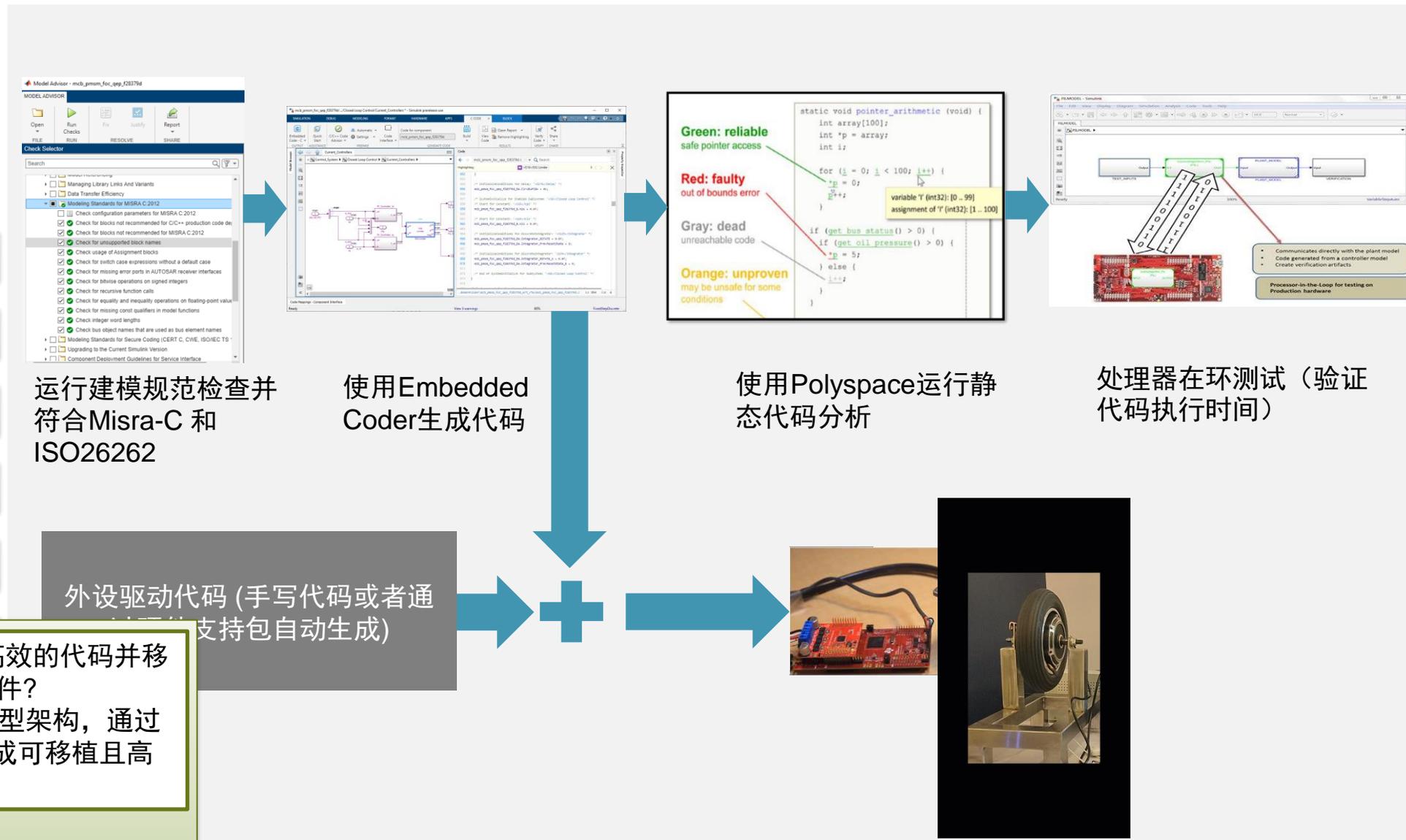
生成C代码或HDL代码，并与外设驱动代码集成



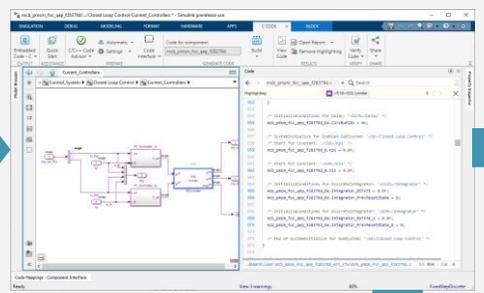


嵌入式工程师

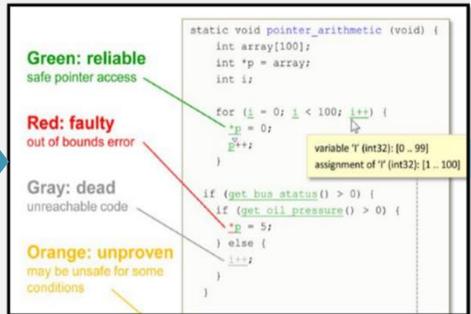
如何生成高效的代码并移植到不同的硬件？
 ▲ 使用分层模型架构，通过Embedded生成可移植且高效的代码。



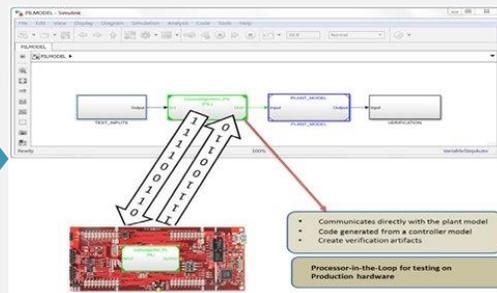
运行建模规范检查并符合Misra-C 和 ISO26262



使用Embedded Coder生成代码

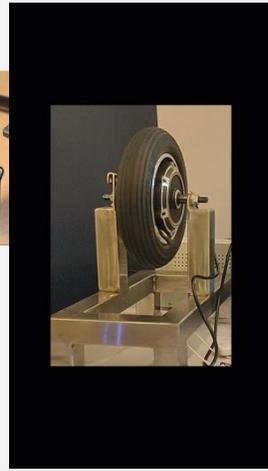
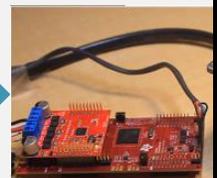


使用Polyspace运行静态代码分析



处理器在环测试 (验证代码执行时间)

外设驱动代码 (手写代码或者通过工具支持包自动生成)



硬件驱动代码——来自硬件支持包或驱动模块



Processor peripheral driver code generation (ADC, PWM, Interrupt trigger, Serial communication)



Embedded Coder Support Package for Texas Instruments C2000 Processors by MathWorks Embedded Coder Team **STAFF**

Generate code optimized for C2000 MCU.

Embedded Coder® Support Package for Texas Instruments C2000™ Processors enables you to run Simulink® models on TI C2000 MCUs. Embedded Coder automatically generates C code for your algorithms and



TI



Field-Oriented Control of PMSM Using NXP™ S32K144 Kit version 1.0 by Shivaprasad Narayan **STAFF**

The workflow demonstrates Field Oriented Control of a Permanent Magnet Synchronous using NXP™ MCSPT1AK144: S32K144 Development Kit

FOC-of-PMSMField-Oriented Control of Permanent Magnet Synchronous Motor Using NXP™ S32K144 Development kitThis example implements a motor control system using the NXP™ MCSPT1AK144 hardware. The



NXP



Demo for Motor Control Deployment on Microchip Controllers version 1.0.0 by Brian McKay **STAFF**

Demo used in MathWorks-Microchip joint webinar: Deploying Motor Control Algorithms on Microchip dsPIC, PIC32, and SAM Controllers.

which includes a dsPIC33E Digital Signal Controller.The demo also require you to download and install the free add-on MPLAB Device Blocks for Simulink: dsPIC, PIC32, and SAM MCU's.View the webinar for a



Microchip



Embedded Coder Support Package for STMicroelectronics STM32 Processors by MathWorks Embedded Coder Team **STAFF**

Generate code optimized for STMicroelectronics STM32 Processor boards



STM



Embedded Coder Support Package for Infineon AURIX TC4x Microcontrollers by MathWorks Embedded Coder Team **STAFF**

Generate code optimized for Infineon AURIX TC4x Microcontrollers



Infineon



HDL Coder Support Package for Xilinx Zynq Platform by MathWorks HDL Coder Team **STAFF**

Generate code for the FPGA portion of the Zynq-7000 SoC.

HDL Coder™ Support Package for Xilinx® Zynq™-7000 Platform supports the generation of IP cores that can be used in FPGA designs using Xilinx Vivado® or Xilinx ISE. When used in combination

Hardware Support



Xilinx
FPGA



Simulink Real-Time Target Support Package by MathWorks Simulink Real Time Target Team **STAFF**

Tools to compile a real-time application that runs on a Speedgoat target computer



Speedgoat

使用Polyspace 执行静态代码分析



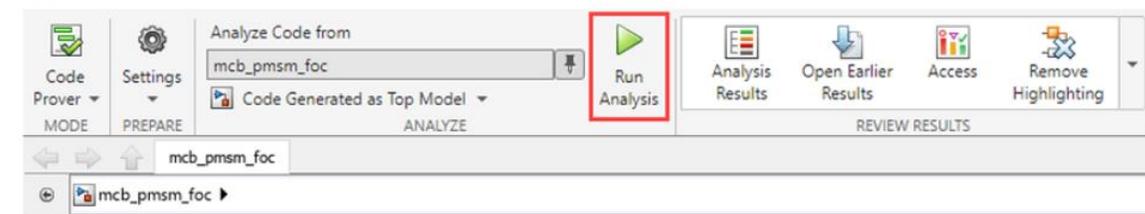
Analyze and Verify Motor Control Algorithms Using Polyspace R2023b

This example uses the Polyspace® static code analysis tools to analyze and verify Simulink® models containing motor control algorithms. Static code analysis is a software verification technique that analyzes source code for quality, reliability, and security without executing the code. This approach uses robust error detection routines (that include checks for critical run-time errors) to identify bugs and defects. This ensures compliance with common coding standards.

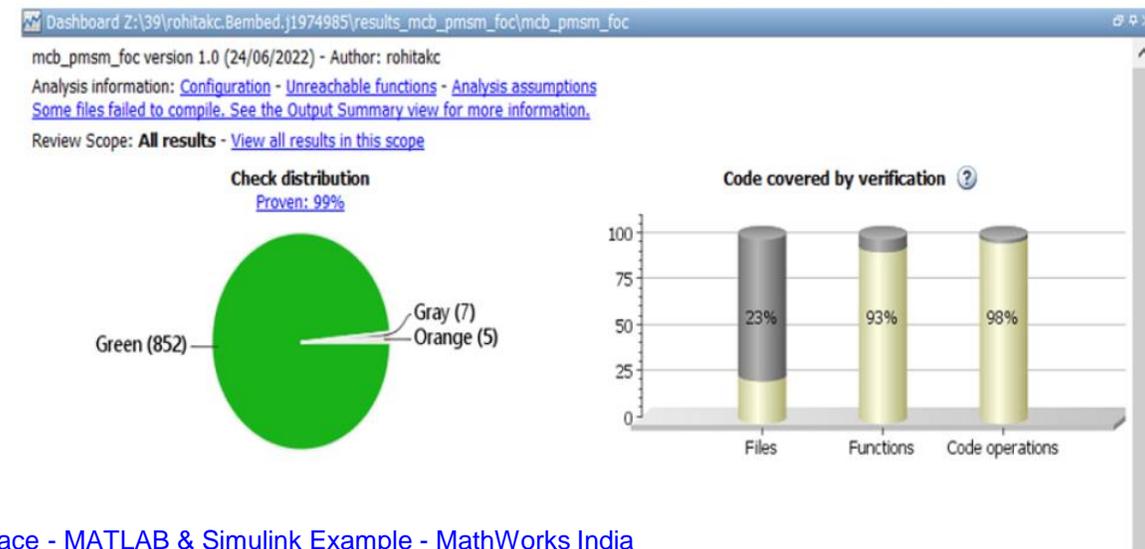
This example uses:

Polyspace Bug Finder
Polyspace Code Prover
Motor Control Blockset

3. Click **Run Analysis** to start running the Code Prover tool.



4. After the tool execution completes, click **Polyspace > Analysis Results** to open the code analysis results in the Polyspace app.



使用参考示例校准位置传感器

模型架构

外设驱动代码

代码部署

静态代码分析

传感器标定

处理器在环(PIL)

AUTOSAR集成

Offset Computation for QEP

Note: This example requires a TI F28069m controller card connected to a PMSM Motor with QEP.

Quadrature Encoder Offset Calibration for PMSM Motor

Calculates the offset between the d-axis of the rotor and encoder index pulse position as detected by the quadrature encoder sensor. The

Quadrature encoder calibration

Hall Sensor Sequence Calibration of BLDC Motor

Calculates the Hall sensor sequence with respect to position zero of the rotor in open-loop control.

Identify Hall sensor sequence

Offset Computation with Hall sensor

Note: This example requires a TI F28069m controller card connected to a PMSM Motor with Hall Sensor.

Hall Offset Calibration for PMSM Motor

Calculates the offset between the rotor direct axis (d-axis) and position detected by the Hall sensor. The field-oriented control (FOC)

Calibrate Hall sensor

Monitor Resolver Using Serial Communication

Operates the resolver sensor to measure the rotor position. The resolver consists of two orthogonally placed stator windings

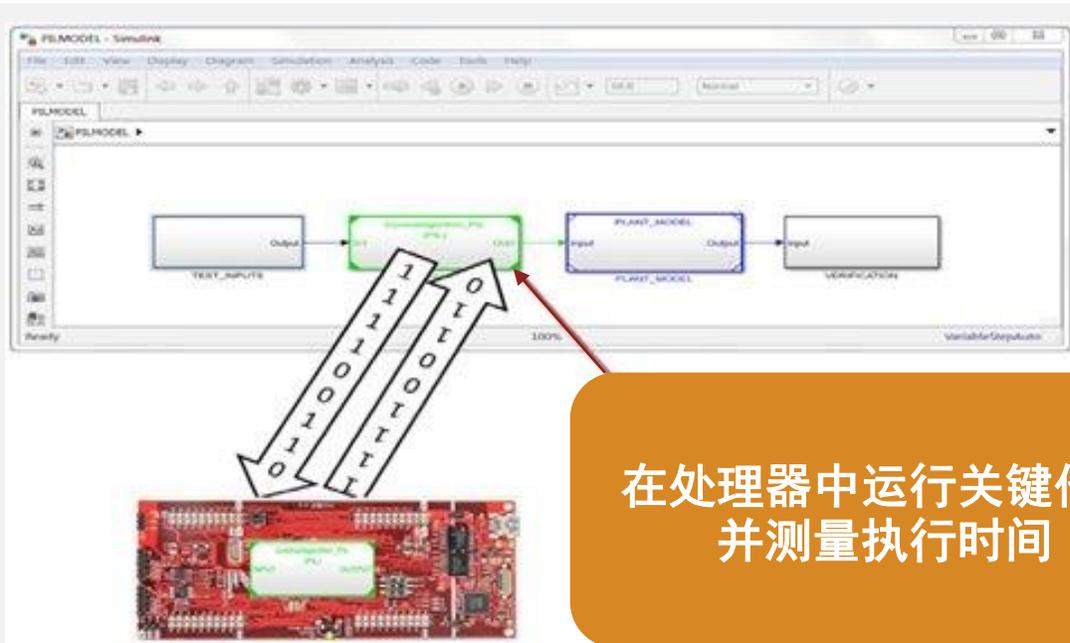
Resolver with Square-pulse carrier frequency

<https://in.mathworks.com/help/mcb/gs/quadrature-encoder-offset-calibration-pmsm-motor.html>

<https://in.mathworks.com/help/mcb/gs/hall-sensor-sequence-calibration-blcd-motor.html>

执行PIL测试

- 模型架构
- 外设驱动代码
- 代码部署
- 静态代码分析
- 传感器标定
- 处理器在环(PIL)
- AUTOSAR集成



在处理器中运行关键代码
并测量执行时间

Report for mcb_pmsm_foc_sim/Current

based on data collected from a SIL or PIL execution. Execution times are calculated from data collected from a SIL or PIL test harness or inside the code generated for each component. See [Code Execution](#)

[Profiling](#) for more information.

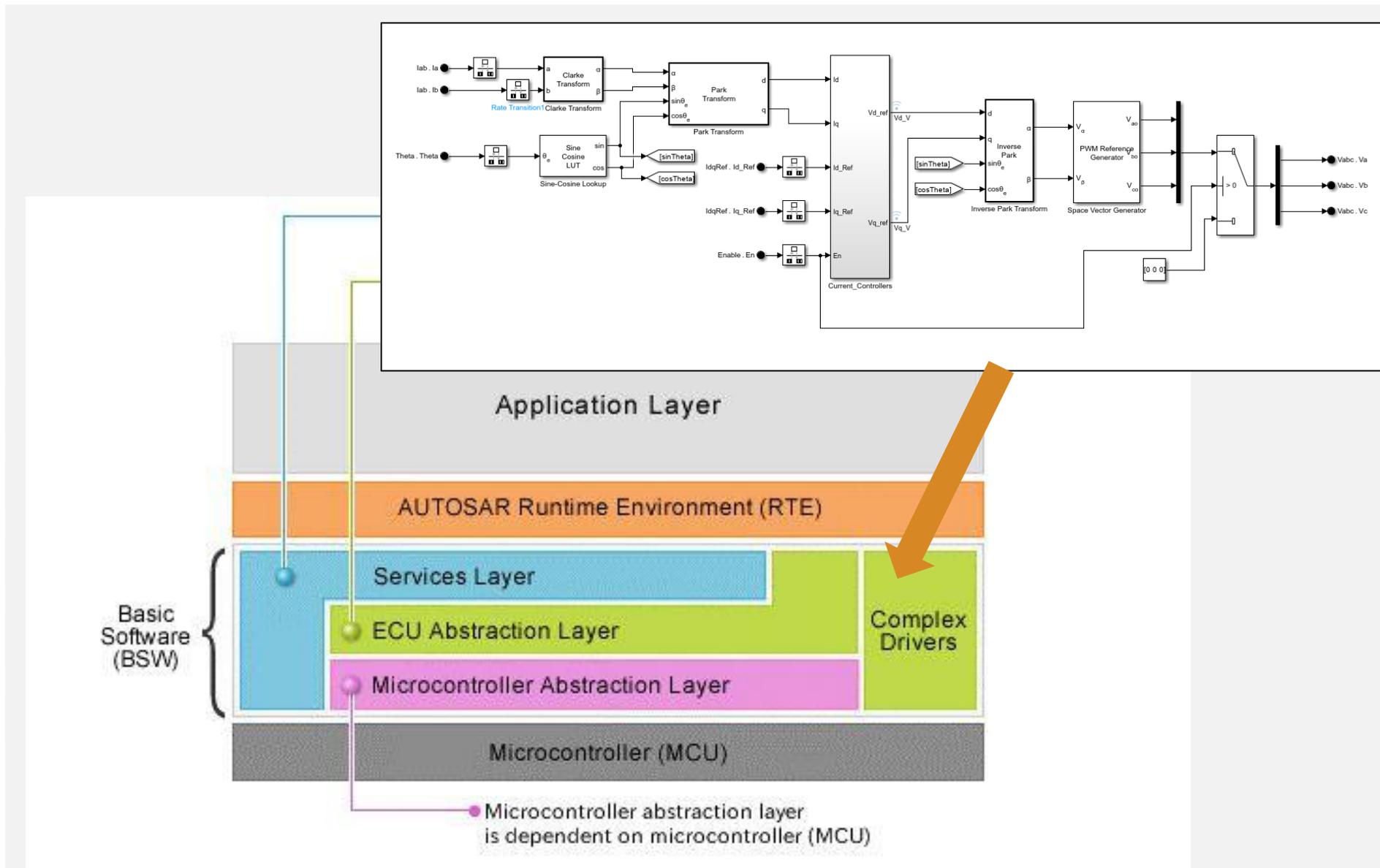
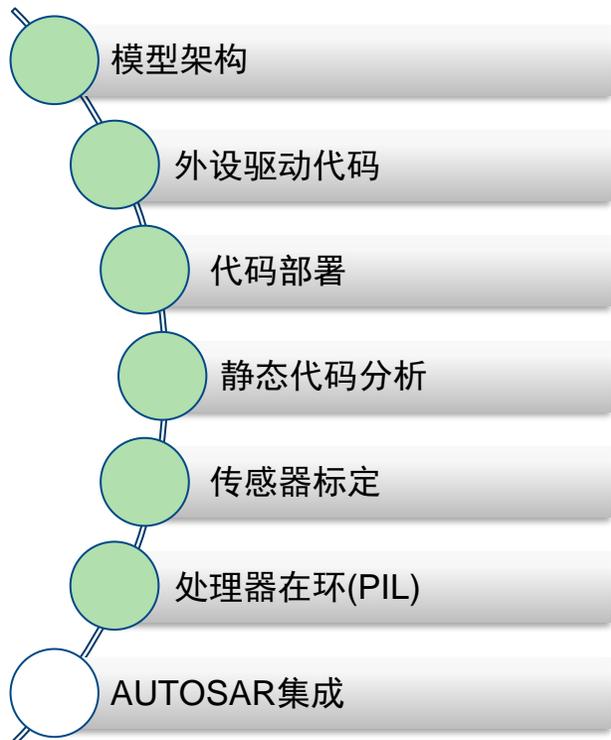
1. Summary

Total time	54531910
Unit of time	ns
Command	report(executionProfile, 'Units', 'seconds', 'ScaleFactor', '1e-09', 'NumericFormat', '%0.0f');
Timer frequency (ticks per second)	2e+08
Profiling data created	15-Jan-2021 13:00:17

2. Profiled Sections of Code

Section	Maximum Execution Time in ns	Average Execution Time in ns	Maximum Self Time in ns	Average Self Time in ns	Calls
[+] Current_initialize	1935	1935	1010	1010	1
[+] Current_step [5e-05 0]	5560	5452	580	580	10001
Current_terminate	140	140	140	140	1

在AUTOSAR架构中集成电机控制算法



在AUTOSAR架构中集成电机控制算法

模型架构

外设驱动代码

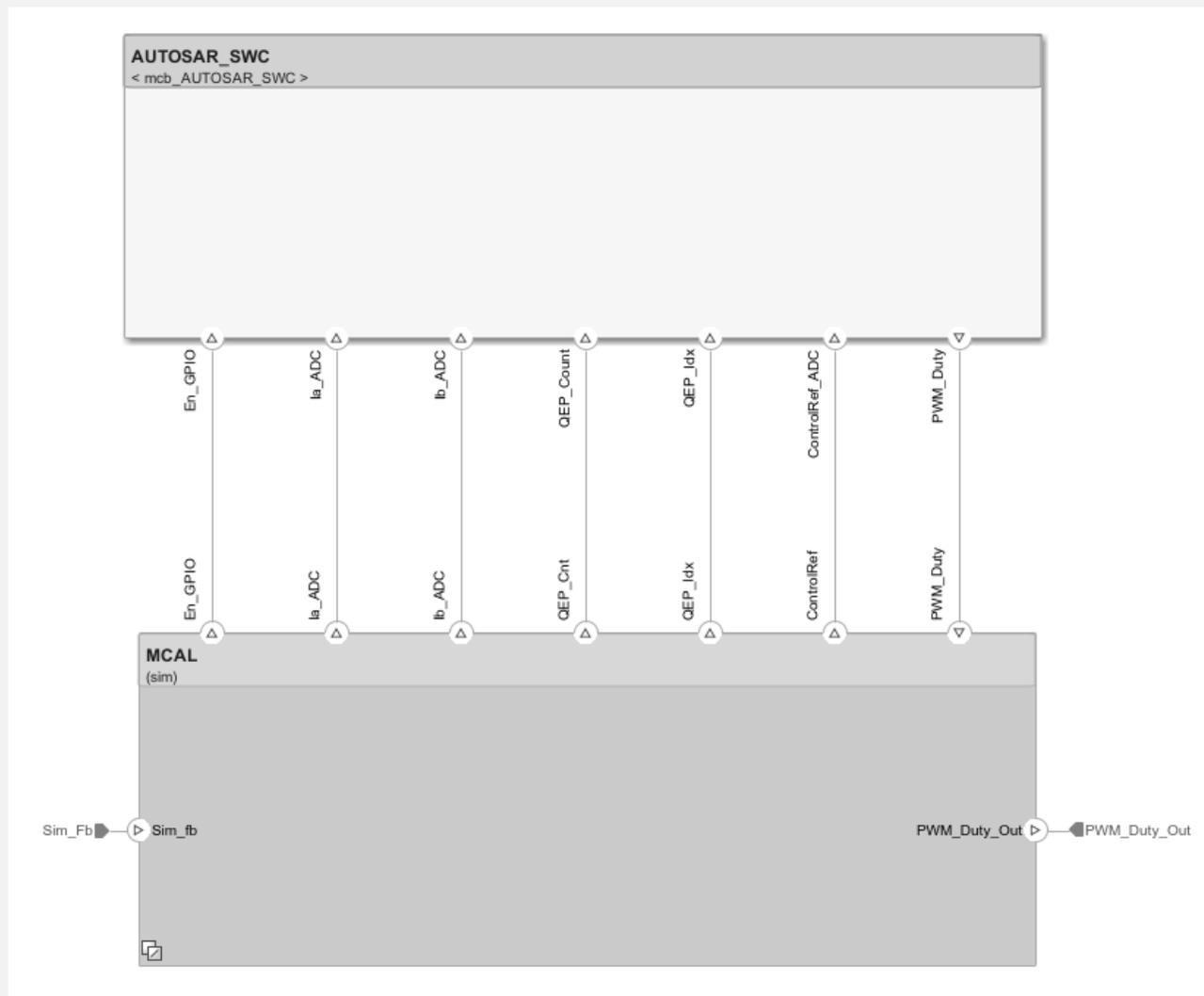
代码部署

静态代码分析

传感器标定

处理器在环(PIL)

AUTOSAR集成



在AUTOSAR架构中集成电机控制算法

模型架构

外设驱动代码

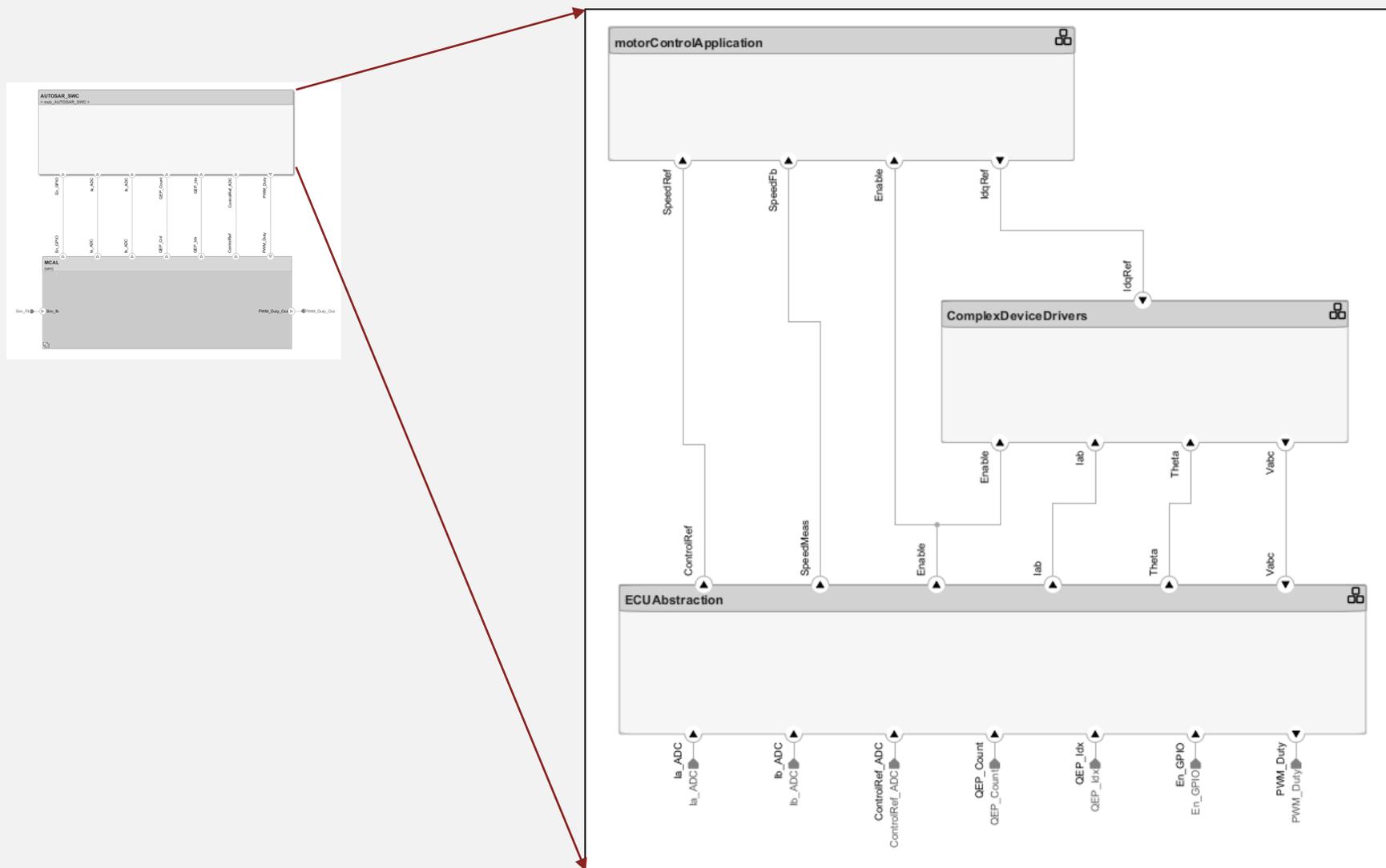
代码部署

静态代码分析

传感器标定

处理器在环(PIL)

AUTOSAR集成



在AUTOSAR架构中集成电机控制算法

模型架构

外设驱动代码

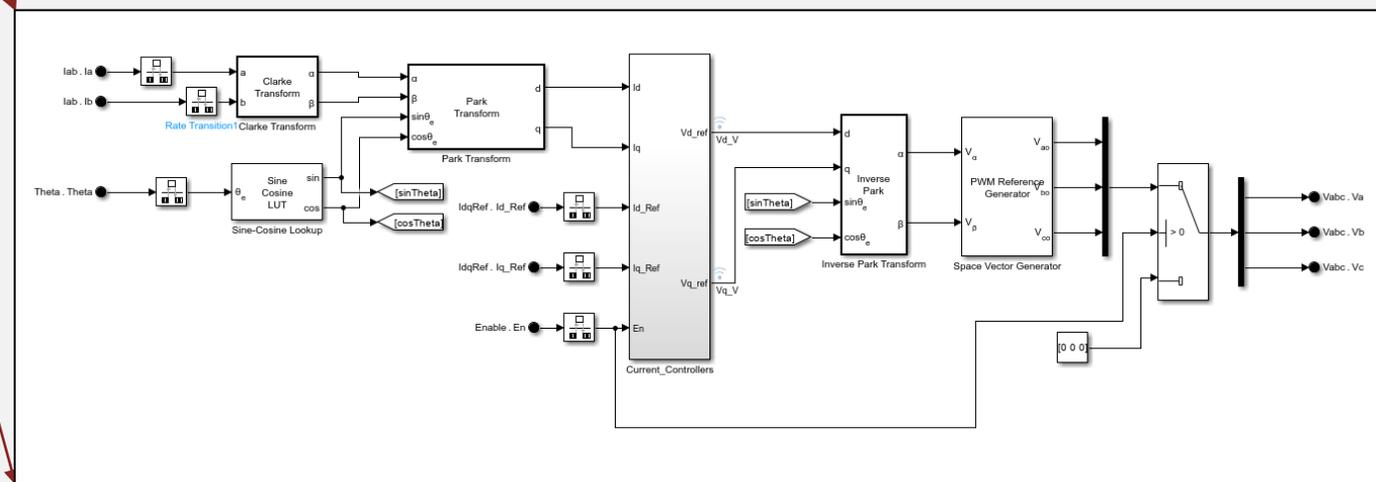
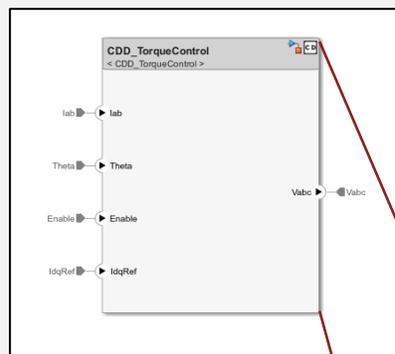
代码部署

静态代码分析

传感器标定

处理器在环(PIL)

AUTOSAR集成



为电机控制组件生成符合AUTOSAR标准的代码和ARXML文件

模型架构

外设驱动代码

代码部署

静态代码分析

传感器标定

处理器在环(PIL)

AUTOSAR集成

The screenshot displays a development environment with three main windows:

- File Explorer:** Shows a project structure with folders like 'stubs', 'Rte_Type.h', 'Rte_CDD_TorqueControl.h', and 'CDD_TorqueControl' (containing .c, .h, and .xml files).
- ARXML Component Description:** Shows XML metadata for 'CDD_TorqueControl' with fields for version (1.17), generation date (Wed Sep 27 11:39:19 2023), and a UUID.
- RTE Header File:** Shows C code for 'Rte_CDD_TorqueControl.h' with preprocessor directives, includes, and function declarations like 'Rte_IRead_CDD_TorqueControl_Step_Theta_Theta'.

总结



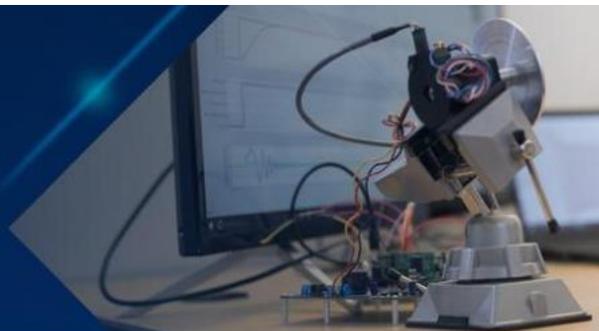
- ✓ 讨论了电机控制工作流程和每个步骤的参考示例
- ✓ 电机参数化的方法及不同的建模保真度
- ✓ 不同的控制策略及其控制环增益调整
- 部署到硬件并进行验证

了解更多

MATLAB and Simulink for Motor Drives and Traction Motors

Develop algorithms and embedded software for motor-inverter control systems

Free trial



How It Works



Design motor control algorithms



Test motor control algorithms



Implement motor control algorithms on hardware

Simulate Motor Control Algorithms

Use MATLAB® and Simulink® to build motor models from libraries of motors, inverters, sources, and loads. Choose the level of fidelity in motor and inverter modeling based on your requirements and simulate motor control algorithms.

- Implement linear lumped-parameter motor models and use average value inverters with Motor Control Blockset™ for fast simulations
- Model and simulate nonlinear motor dynamics and ideal or detailed switching in the inverter using Power Systems Simulation Onramp
- Parametrize motor models to capture motor dynamics with the help of instrumented tests or import parameters from a database or finite element analysis



Motor Control Design with MATLAB and Simulink

MathWorks Videos

Suggest a video



Understanding Field-Oriented Control | Motor Control, Part 4



Reinforcement Learning for Developing Field-Oriented Control



Motor Control, Part 3: BLDC Speed Control Using PWM

» View all MathWorks videos

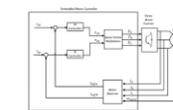
MATLAB 和 Simulink 咨询服务

搜索 MathWorks.com

总览 | 已验证的解决方案

电机控制开发

电机仿真和控制是能源生产、汽车、航空航天、工业自动化等行业的一项重要技术。电机系统建模常用于优化逆变器和电机尺寸，开发复杂的控制算法（如磁场定向控制），以及分析系统配置和性能。复杂的电机控制技术可以使电机一直在所需的工作包线内运行，从而实现平滑的扭矩应用、精确的加速控制和更高的电机效率。为了实现电机控制，必须基于电机和逆变器系统的详细且精确的被控对象模型开发控制算法。



有问题吗?

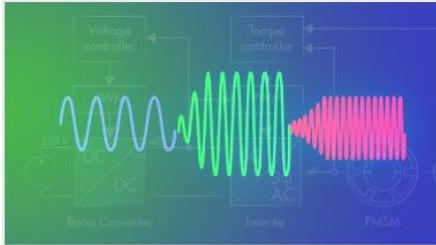
» 联系咨询服务

联系咨询服务



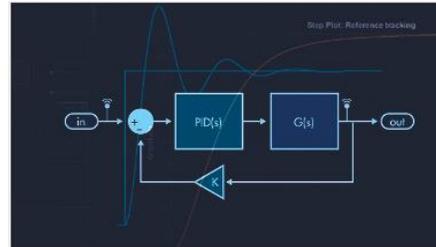
通过与数百家公司的广泛合作，MathWorks Consulting Services 积累了丰富的行业经验，并积淀了丰富的专业技术知识，可帮助您开发和测试适合您应用的电机控制算法。

让您的团队能够开发电机控制



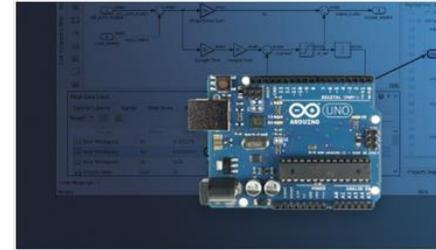
Power Electronics Control Design with Simulink and Simscape

Learn to model power electronic systems in the Simulink environment using Simscape Electrical™ and to design control with Simulink Control Design.



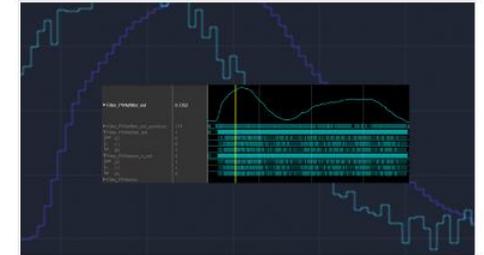
Control System Design with MATLAB and Simulink

Learn to design and model control systems with Simulink. Topics include system identification, parameter estimation, control system analysis, and response optimization.



Embedded Coder for Production Code Generation

Develop Simulink models for deployment in embedded systems. Topics include code structure and execution, code generation options and optimizations, and deploying code to target hardware.



Generating HDL Code from Simulink

Learn to prepare Simulink models for HDL code generation, generate HDL code and testbench for a compatible Simulink model, and perform speed and area optimizations.



Power Electronics Simulation Onramp

5 modules | 1 hour | Languages

Learn the basics of simulating power electronics converters in Simscape.



Circuit Simulation Onramp

7 modules | 2 hours | Languages

Learn the basics of simulating electrical circuits in Simscape.

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- 更高的质量
- 降低风险
- 改进协作



我们期待与您合作!

<https://ww2.mathworks.cn/services/consulting.html>

MATLAB EXPO

谢谢



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