# Virtual Design of Electrified Powertrain Systems

## Calibrating PMSM Torque Control Lookup Tables Using Model-Based Calibration

**MathWorks Automotive Conference**
**Plymouth, MI**
**April 30th, 2019**

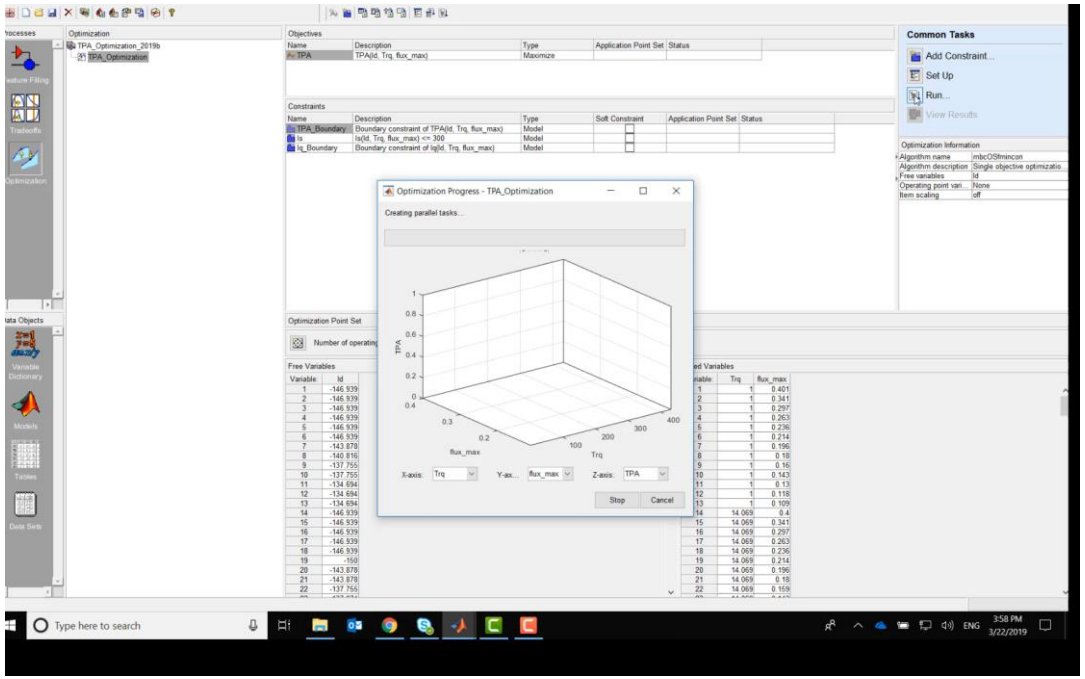
Dakai Hu, Ph.D -- MathWorks Application Engineering
Javier Gazzarri, Ph.D -- MathWorks Application Engineering

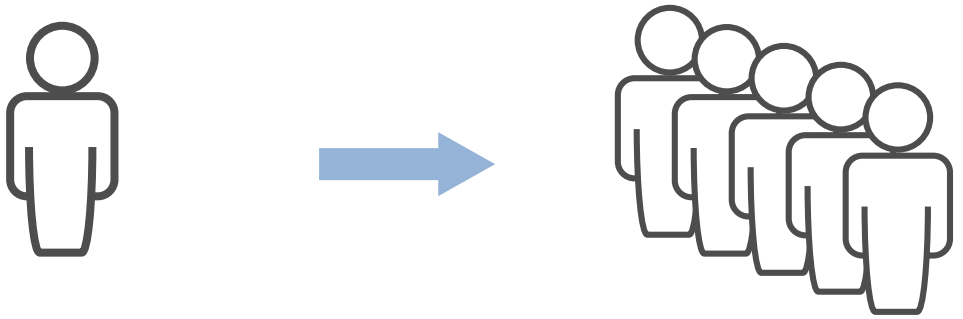
# PMSM Calibration

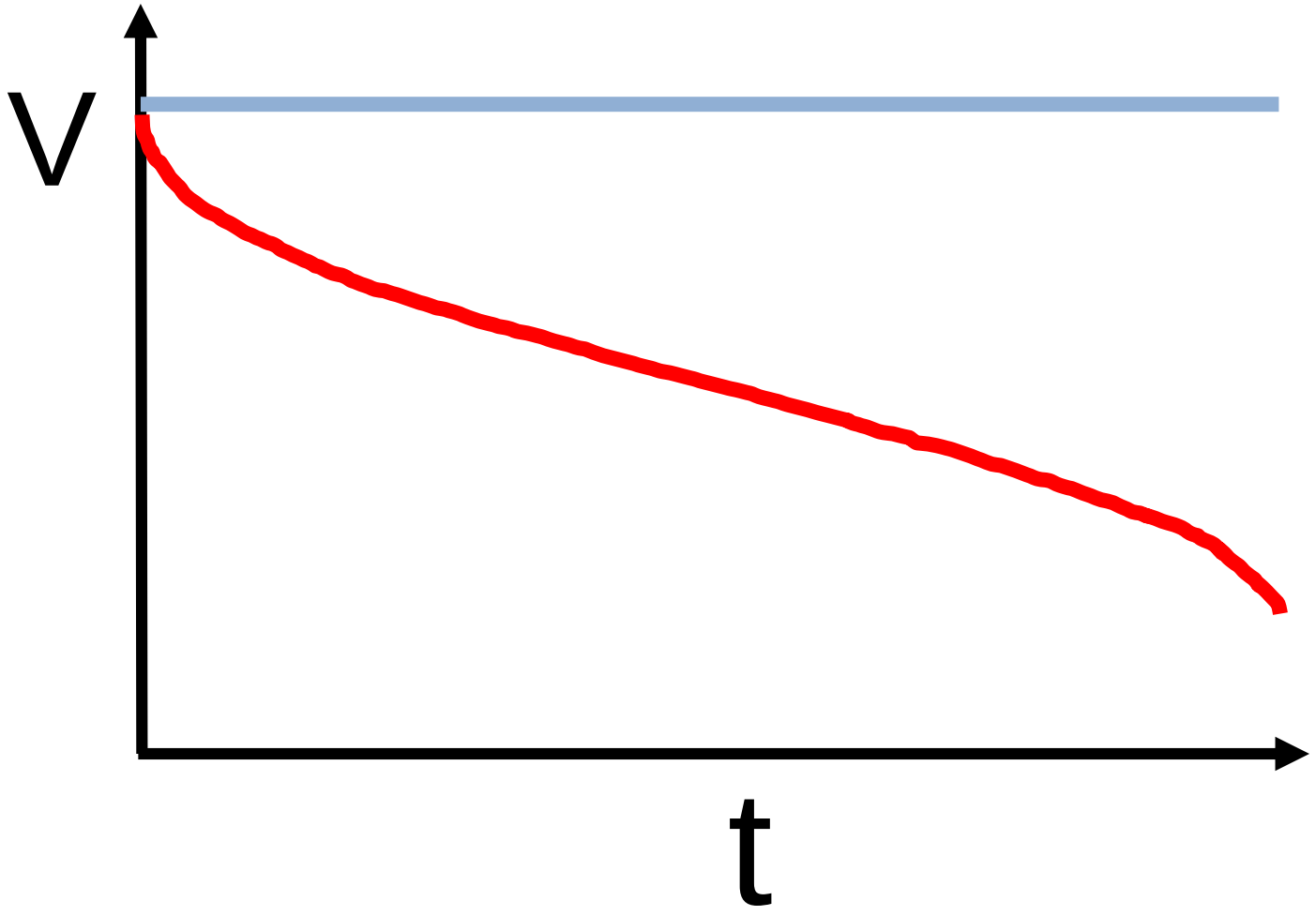
Productive

Automated

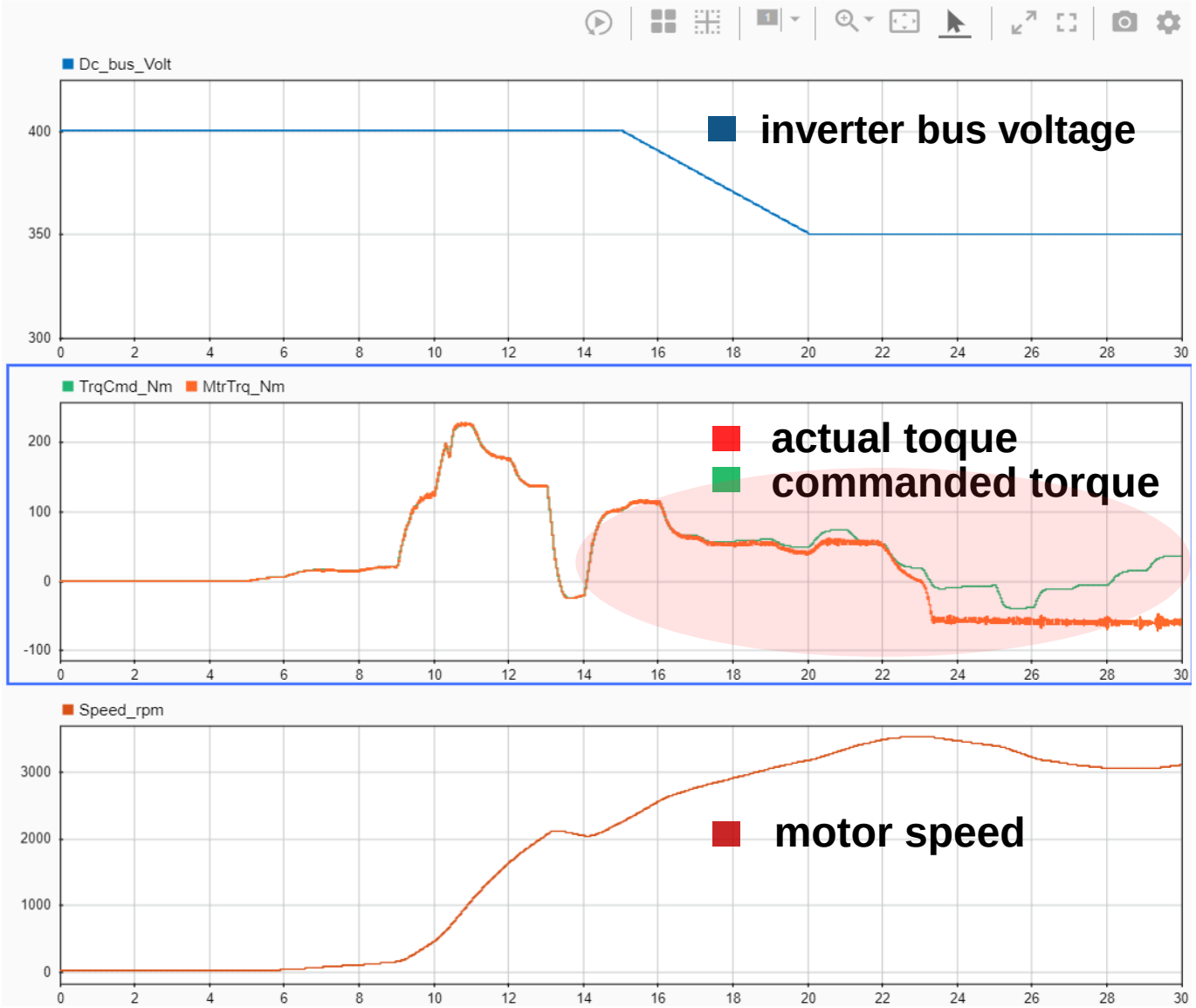
Scalable



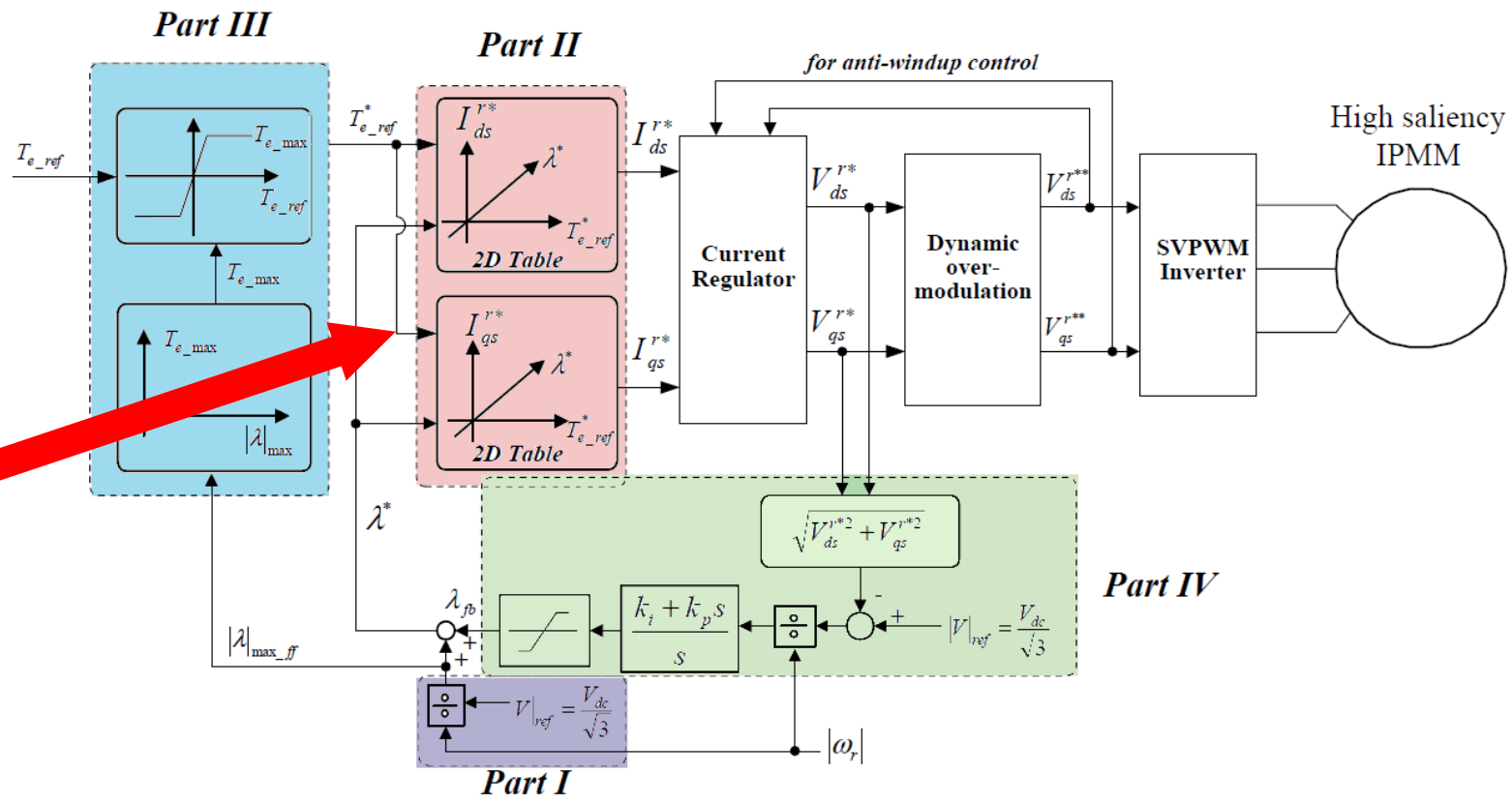

V
t

# Effect of Inverter Bus Voltage Drop on Torque Control



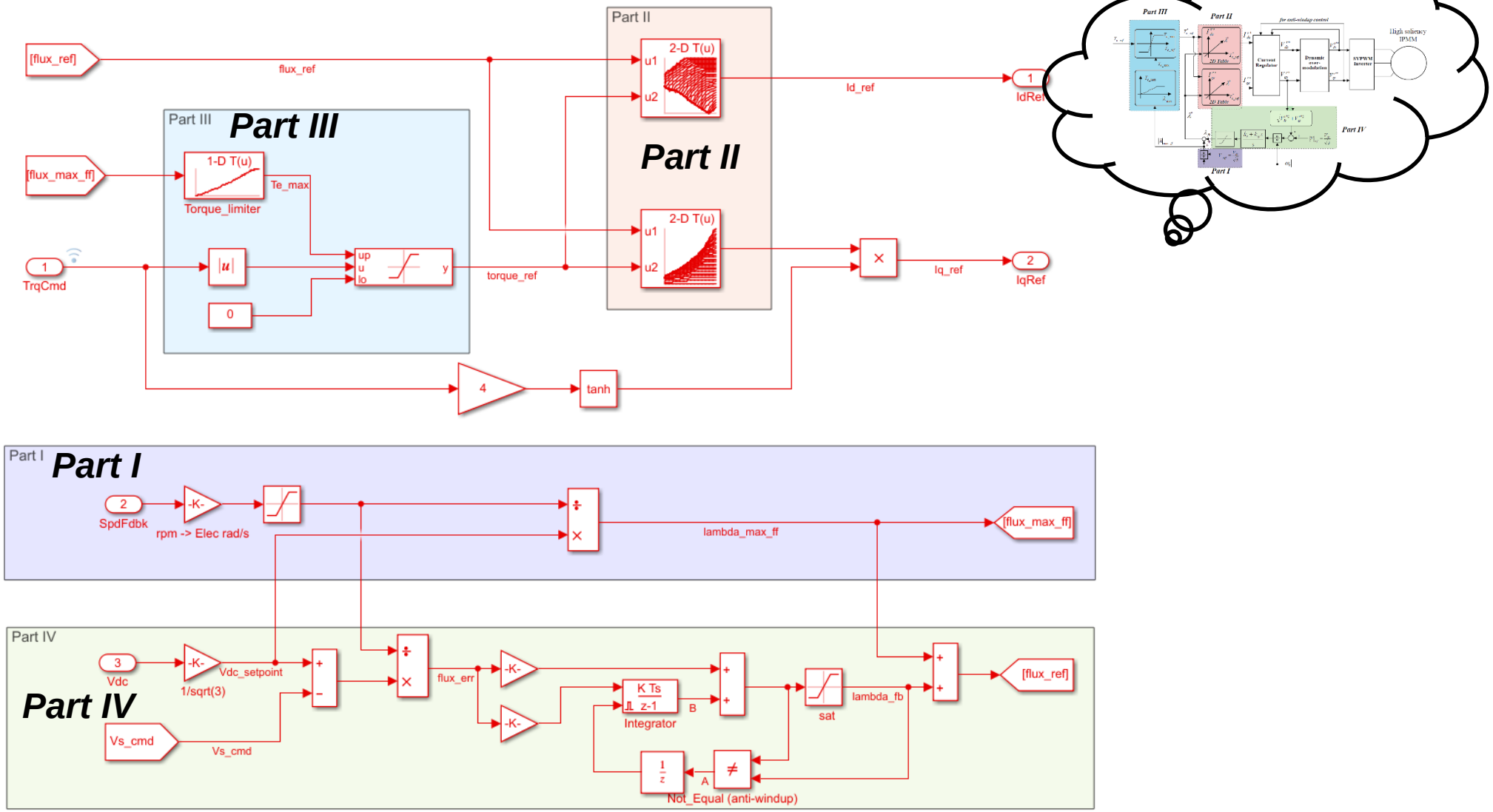
# Flux-Based Calibration Tables

- Flux levels are adjusted based on variation of inverter bus voltage
- Key enabler: flux-based $i_d$ and $i_q$ tables

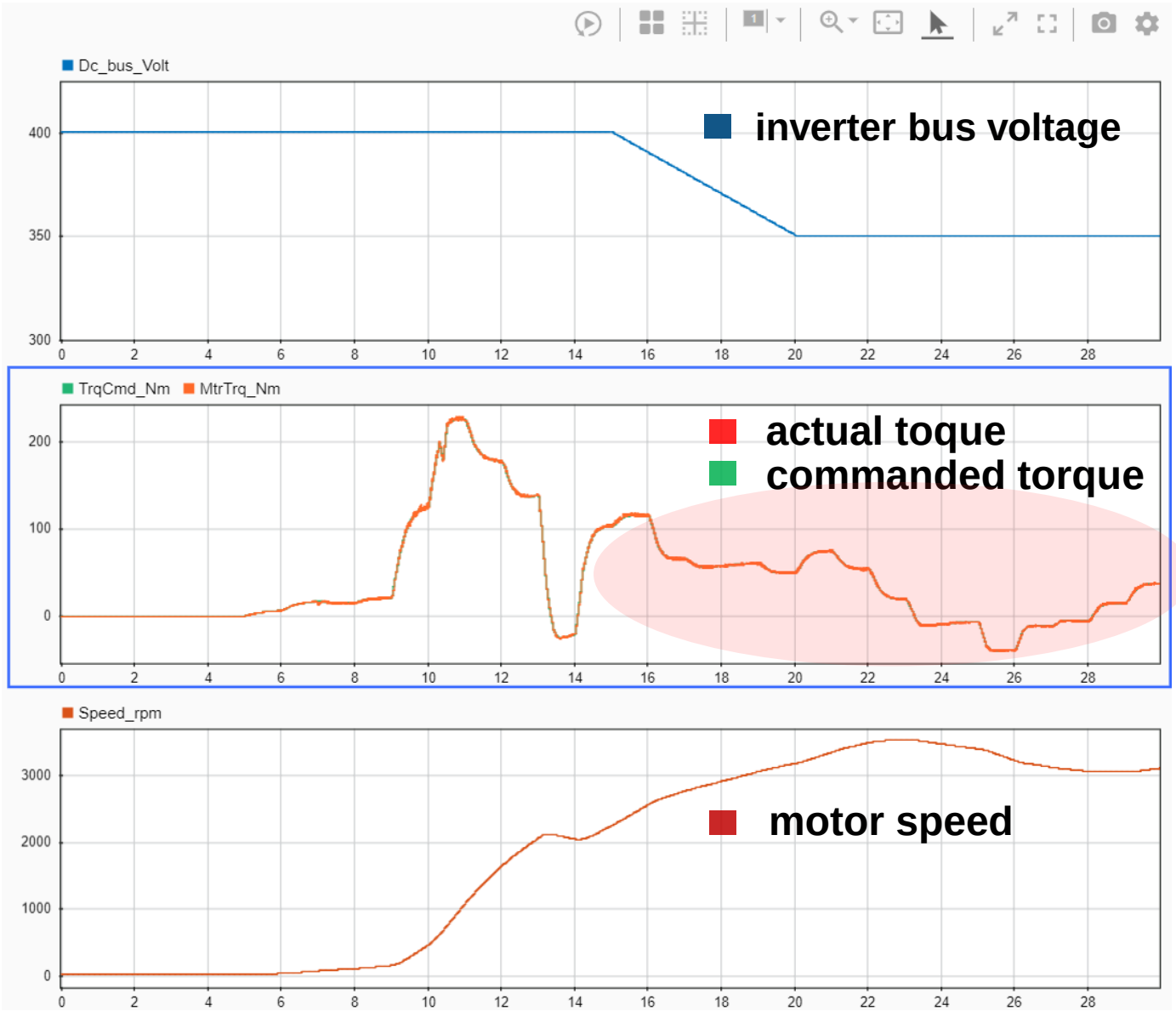



Reference: Bon-Ho Bae, Patel N., Schulz, S., Seung-Ki Sul , “New Field Weakening Technique for High Saliency Interior Permanent Magnet Motor” 38th IAS Annual Meeting. Conference Record of the Industry Applications Conference, Vol. 2, pp.898-905, 2003.

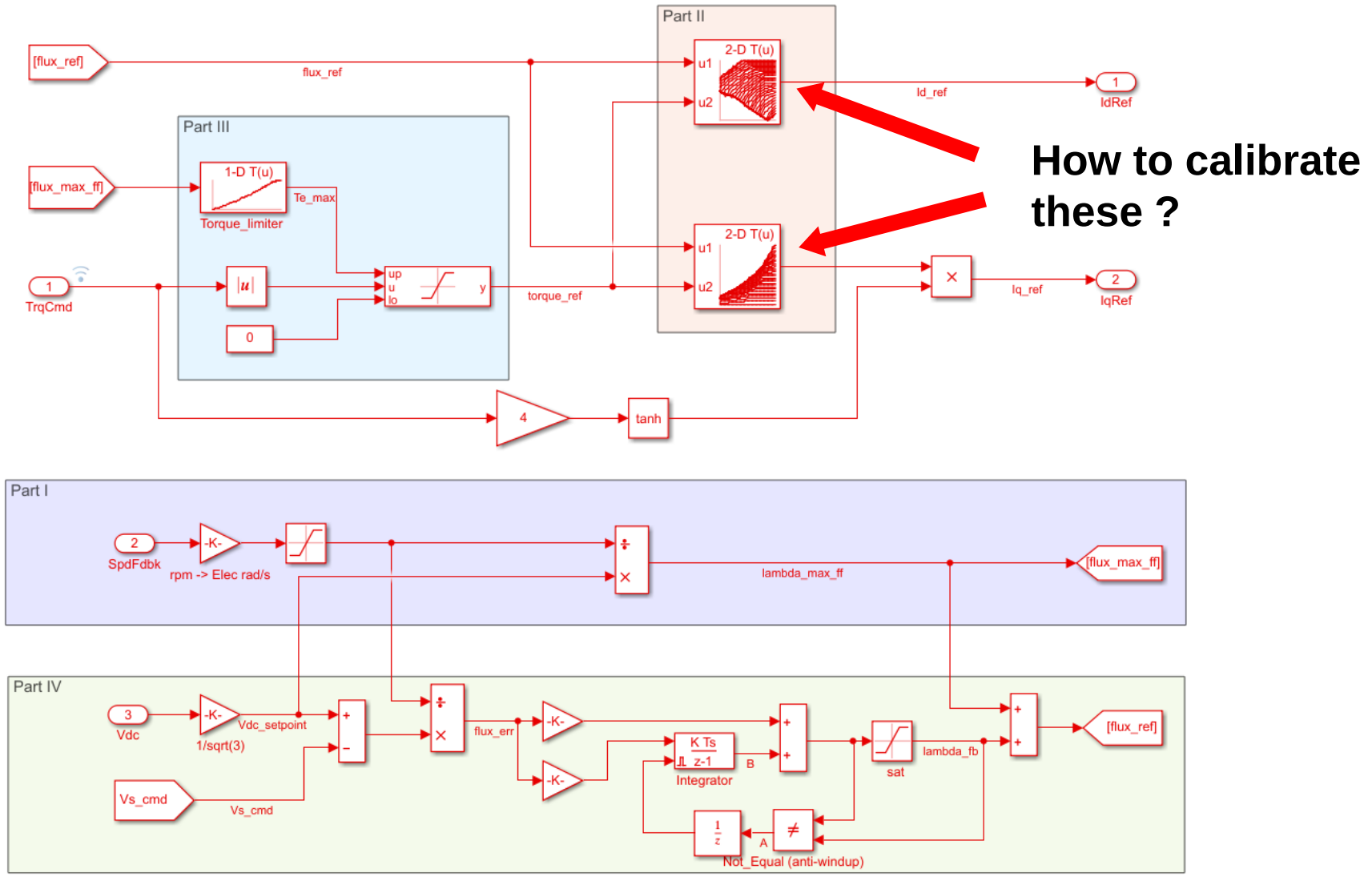
# Simulink Implementation of Flux-Based Calibration Tables



# Flux-Based Calibration Tables – Simulation Results



# Flux-Based Calibration Tables

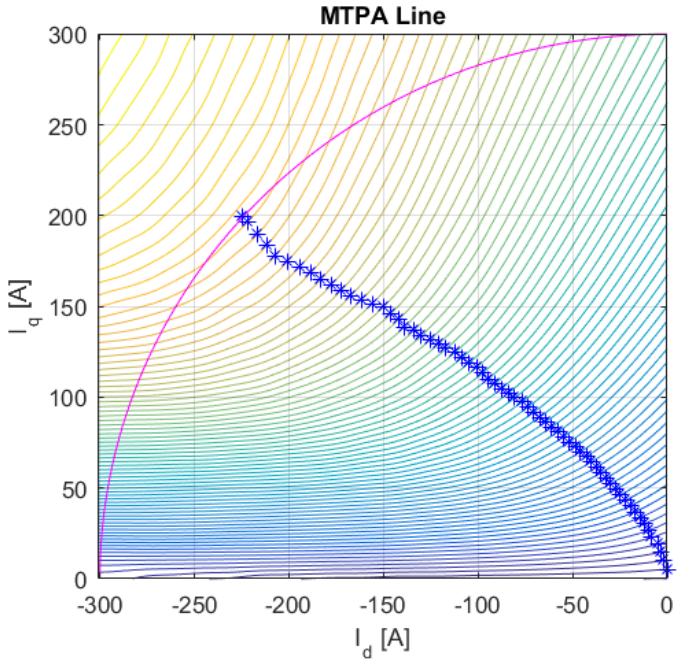


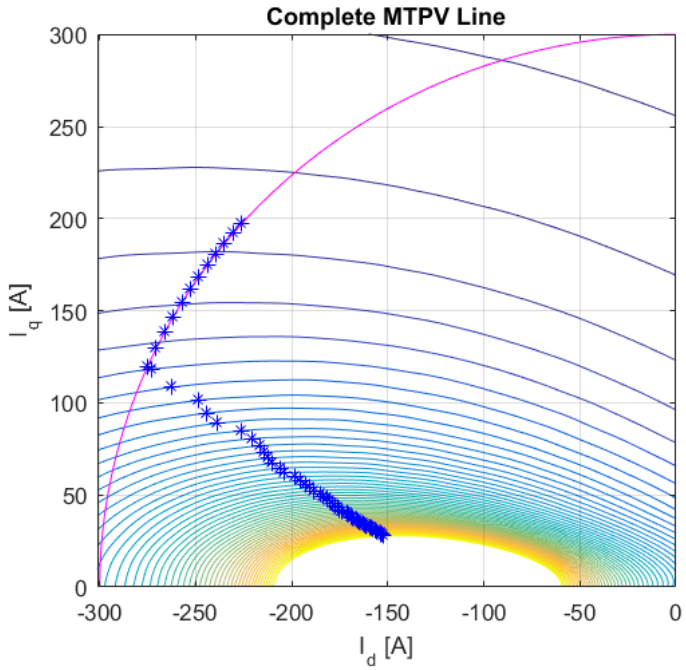
# Different Ways to Calibrate Flux-Based Tables

**Manual & Rule-Based Calibration**

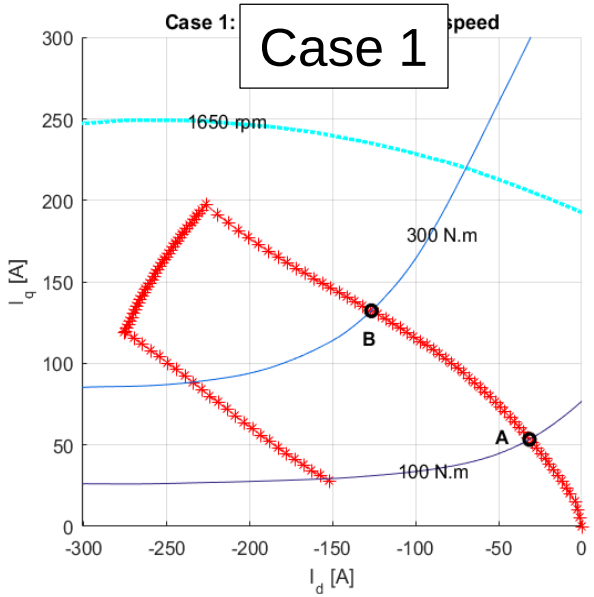
**Model-Based Calibration**

# Manual

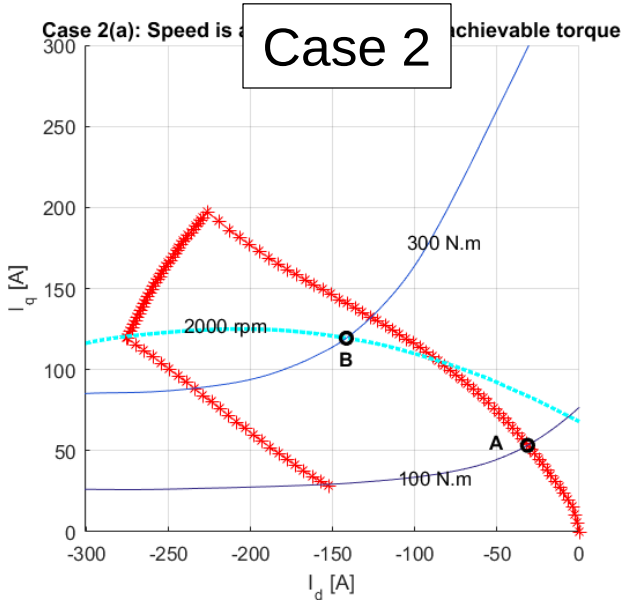


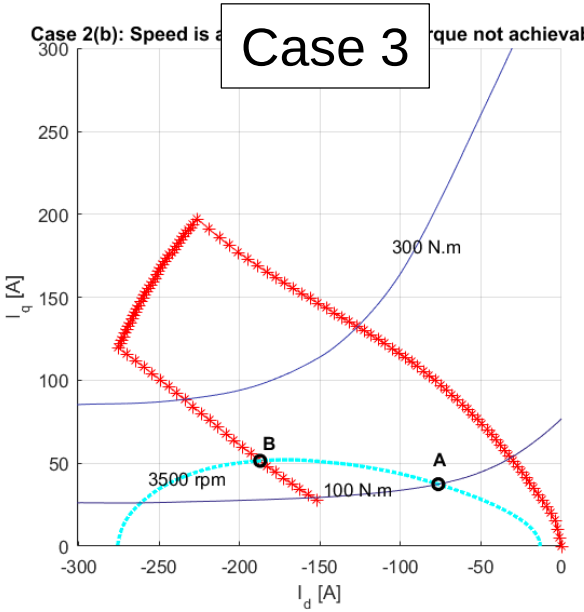

Case 1




Case 2




Case 3

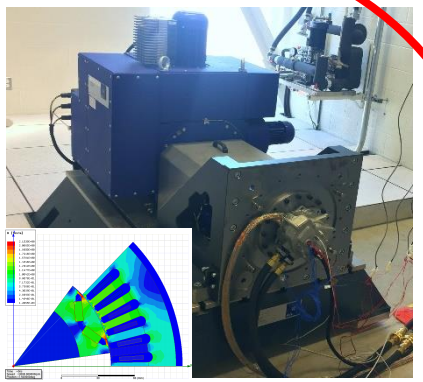


# Model-Based Calibration

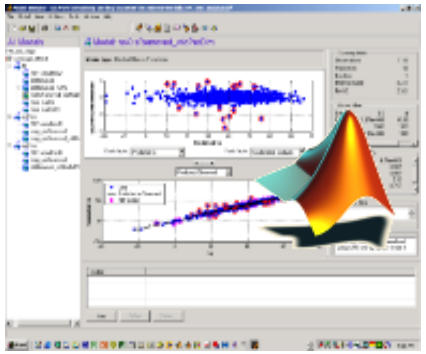
## What is Model-Based Calibration (MBC)?

- Workflow for calibrating parameters for plant models and control systems
- Includes steps for
  - Design of Experiments (DoE)
  - Model fitting and optimization
  - Design parameter tradeoff studies
  - Calibration generation for lookup tables

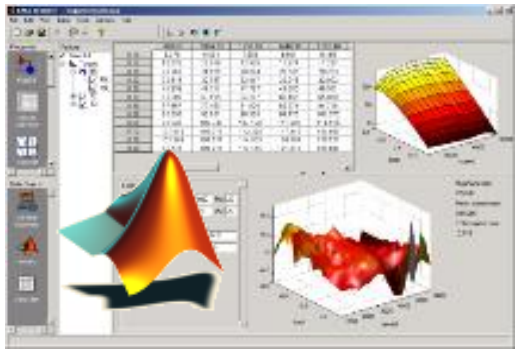
# Model-Based Calibration Workflow ➔ MBC Toolbox



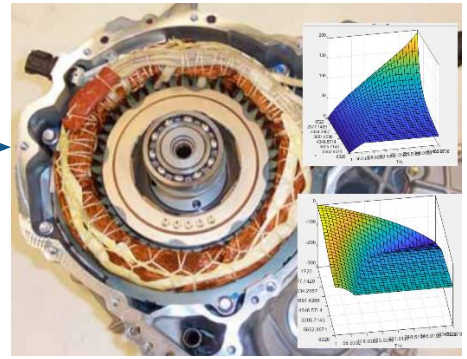
Data Collection



Data Modeling

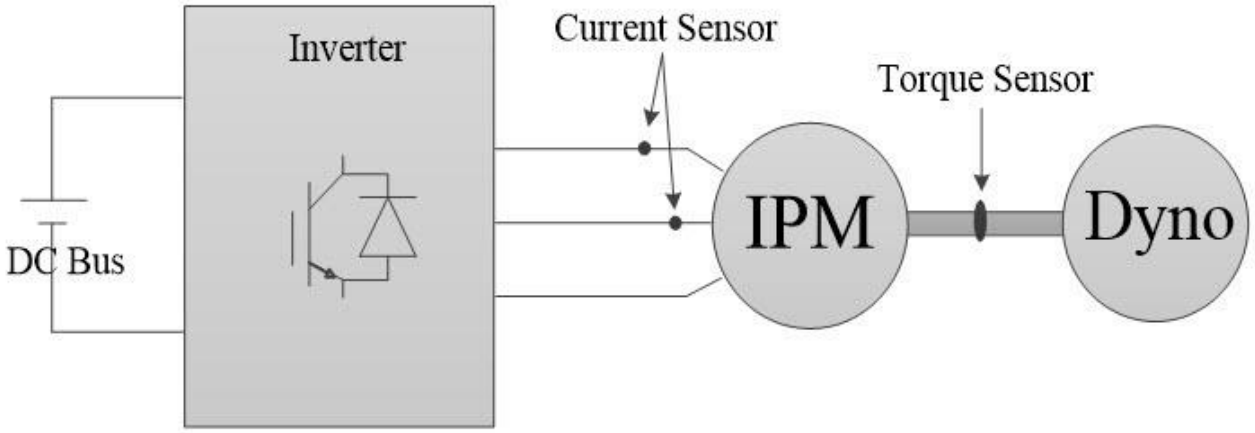


Calibration

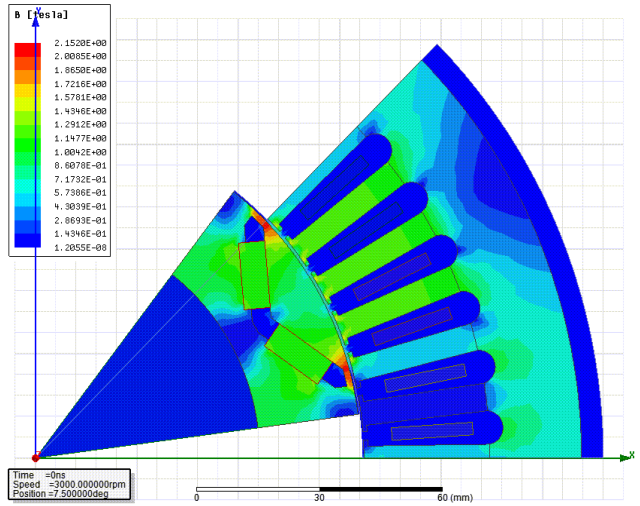


Implementation

# Data Collection (PMSM Characterization)



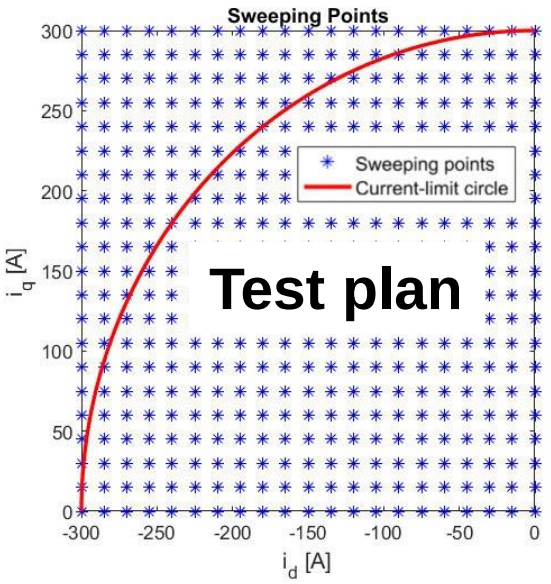

Dyno

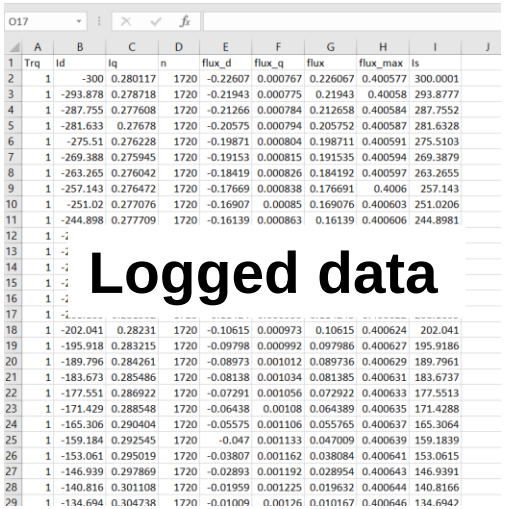


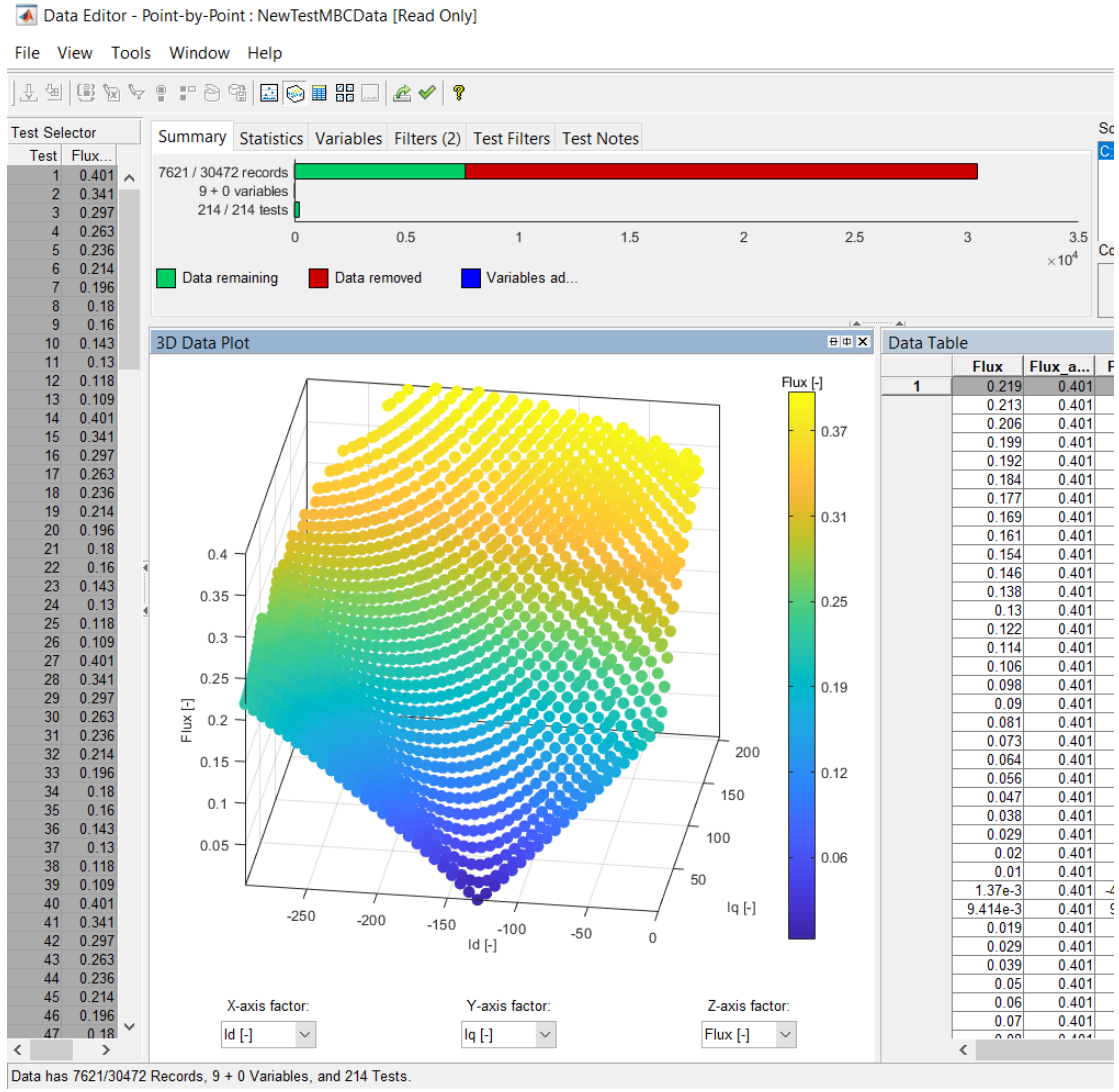

FEA

Reference: D. Hu, “Designing a Torque Controller for a PMSM through Simulation on a Virtual Dynamometer”, MathWorks technical article.
https://www.mathworks.com/company/newsletters/articles/designing-a-torque-controller-for-a-pmsm-through-simulation-on-a-virtual-dynamometer.html

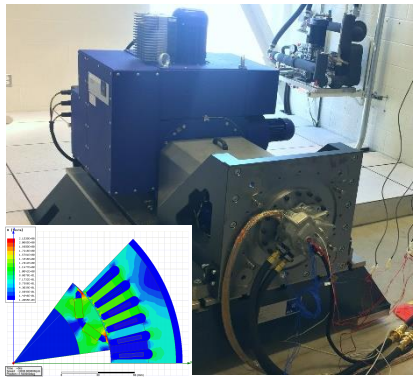
# Data Collection (PMSM Characterization)



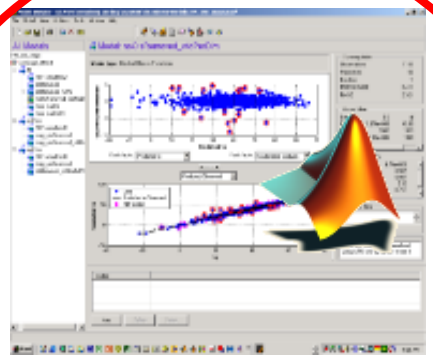



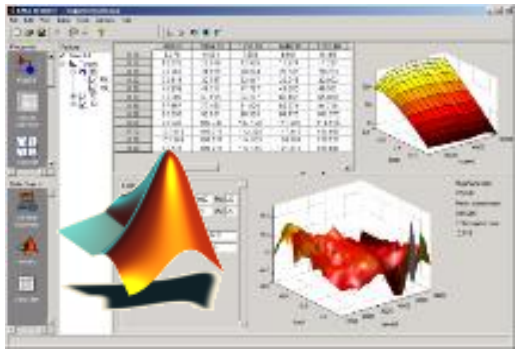
# Model-Based Calibration Workflow



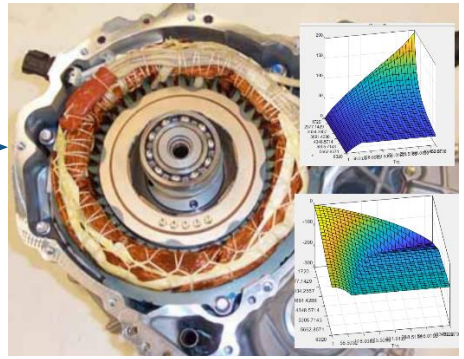
Data Collection



Data Modeling



Calibration



Implementation

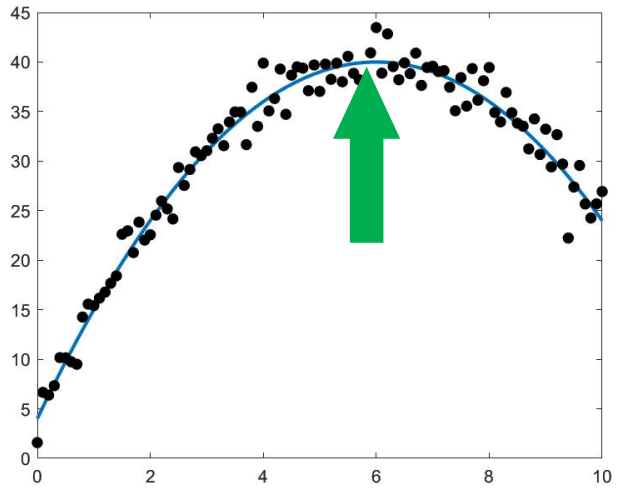
# Why Data Modeling?

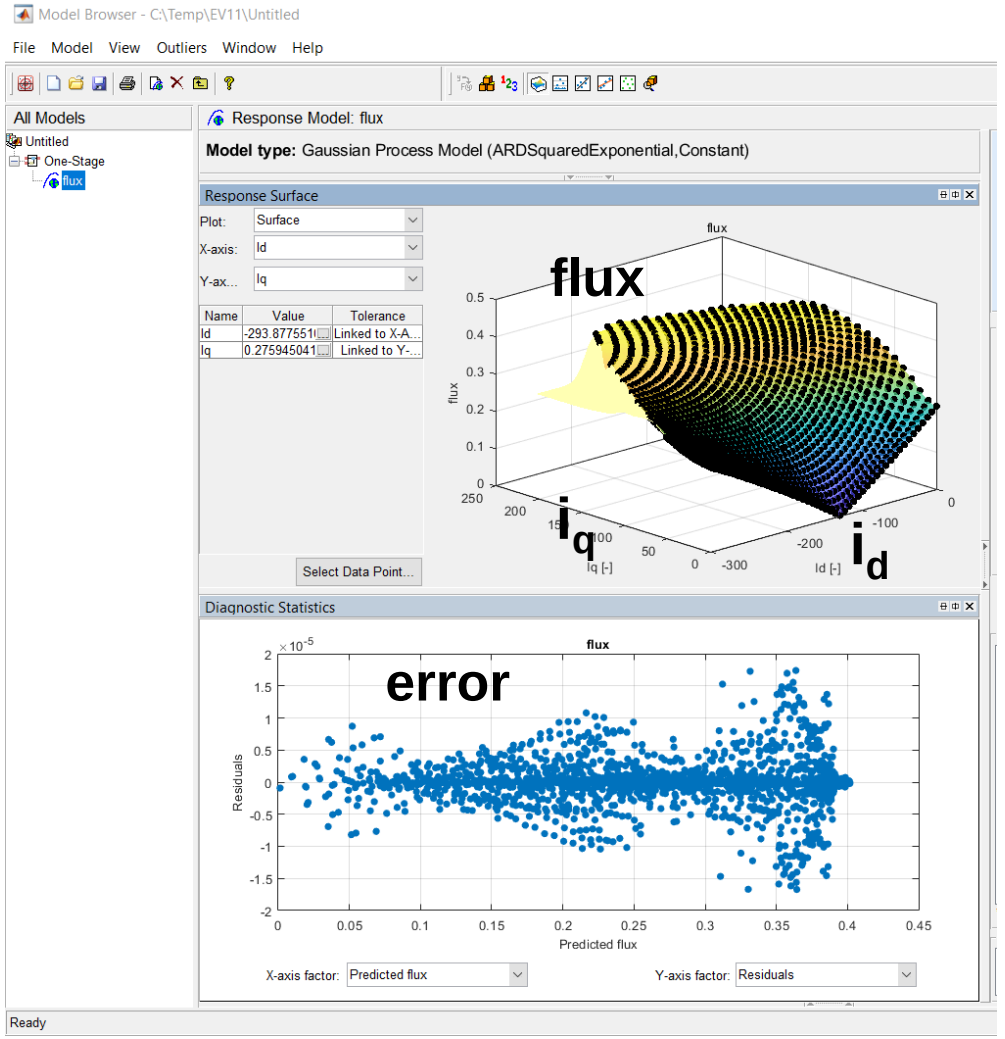
Statistical models that map input variables to output responses

- Polynomials
- Radial Basis Functions
- Gaussian Process Models

Rationale

- Smooth raw data
- Interpolate between data points
- Reduce number of data points
- **Enable fast optimization**



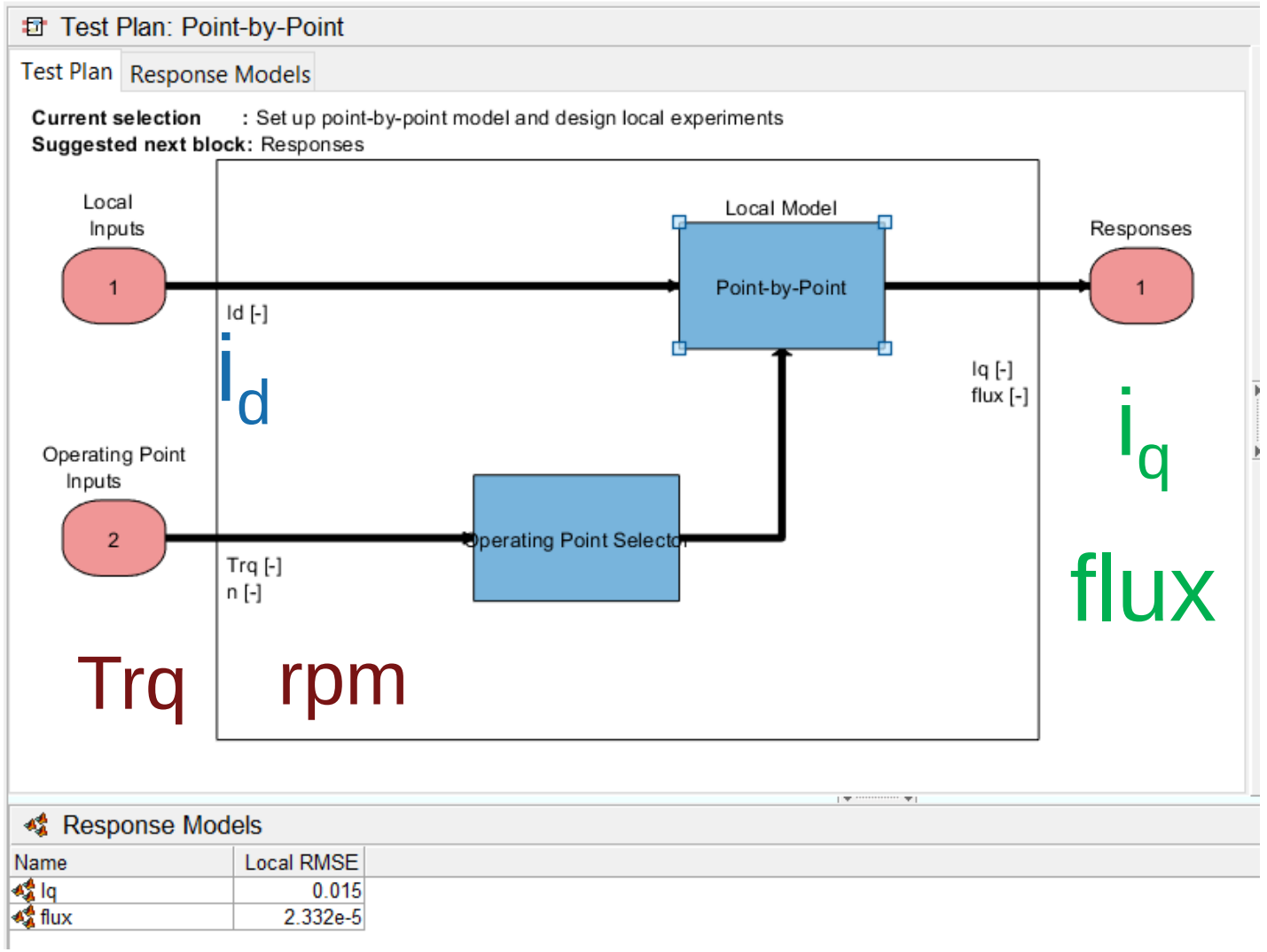
# Data Modeling

Operating point Trq rpm

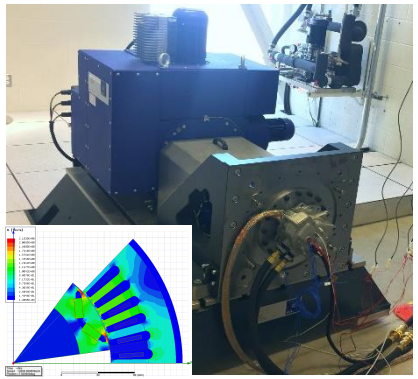
input $i_d$

map

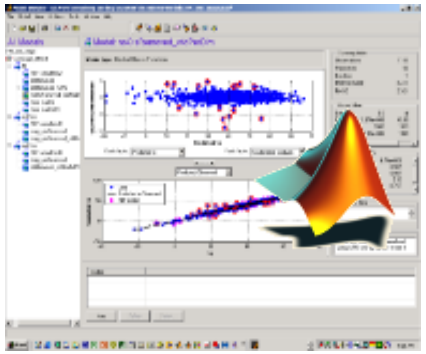
response $i_q$ flux



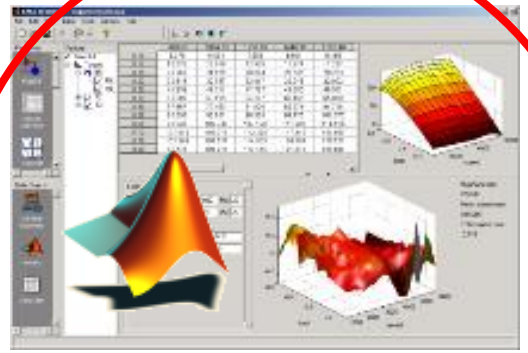
# Model-Based Calibration Workflow



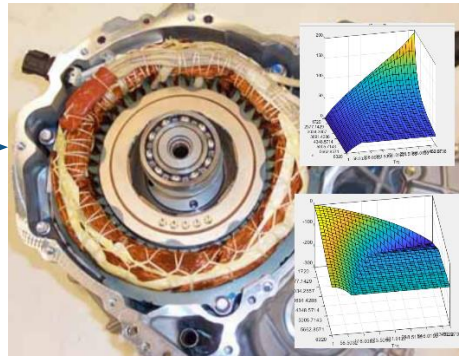
Data Collection



Data Modeling



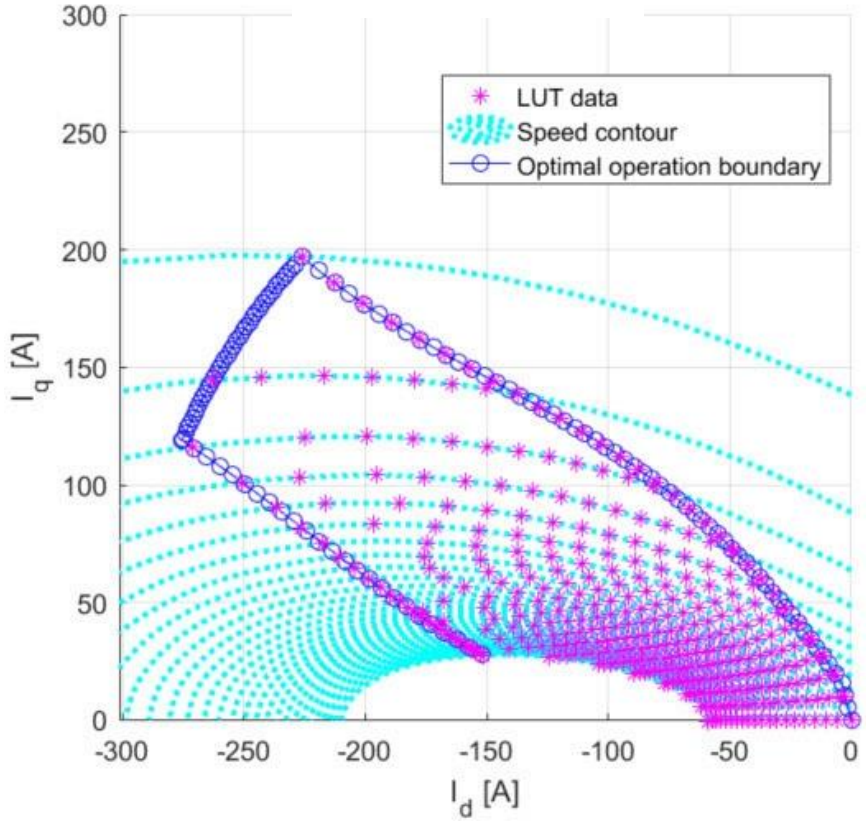
Calibration



Implementation

# Calibration

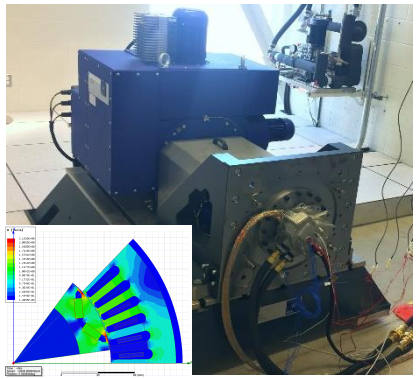
Given the fitted model, where is the best (id, iq) operating points that can achieve pre-set optimization objective while satisfying certain physical constraints.



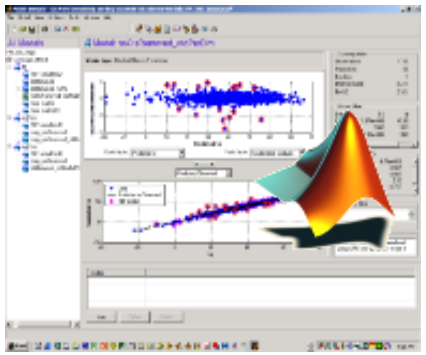

Optimization objective: maximize efficiency (Torque per Amp)

Constraints: current <= current_max
flux <= flux_allowed

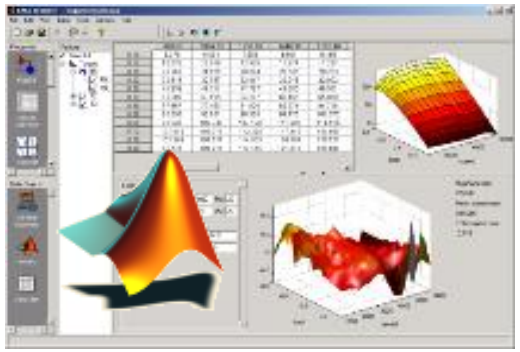
# Model-Based Calibration Workflow



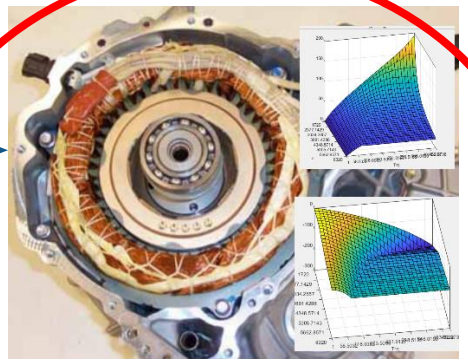
Data Collection



Data Modeling

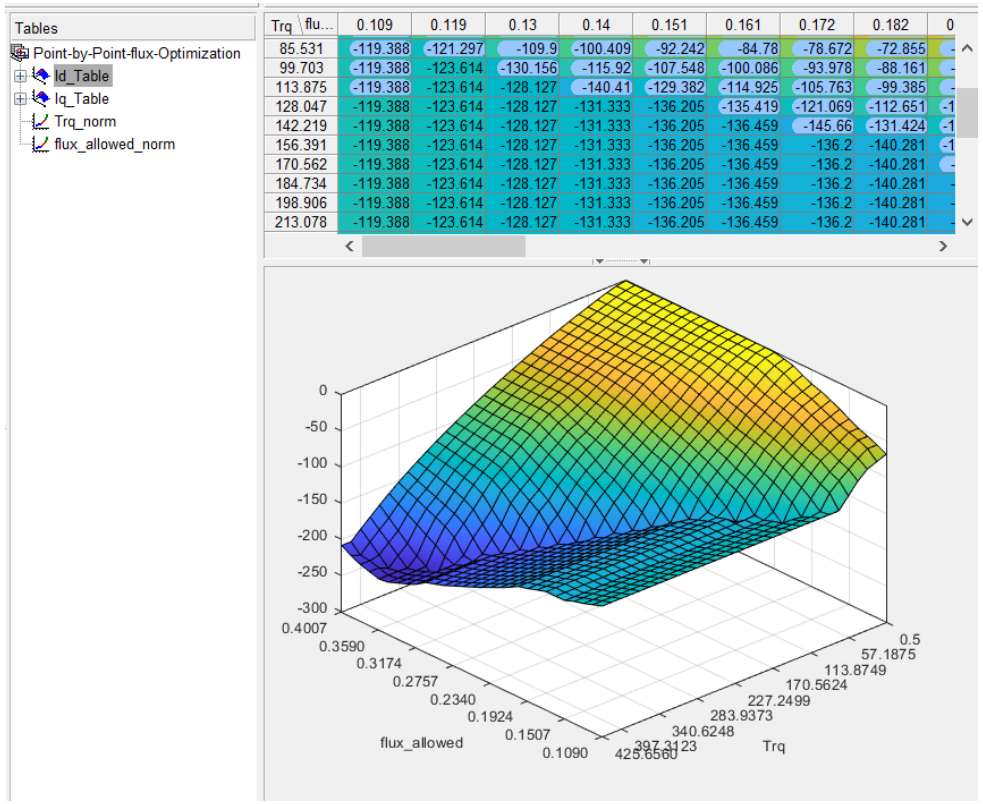


Calibration

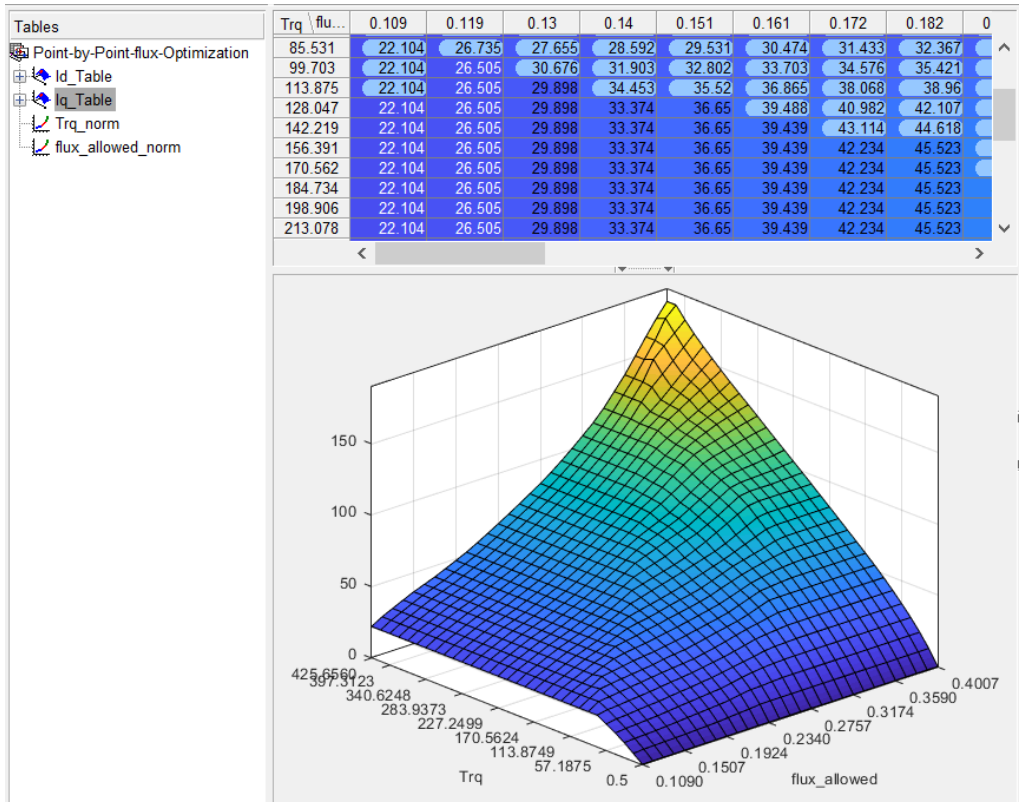


Implementation

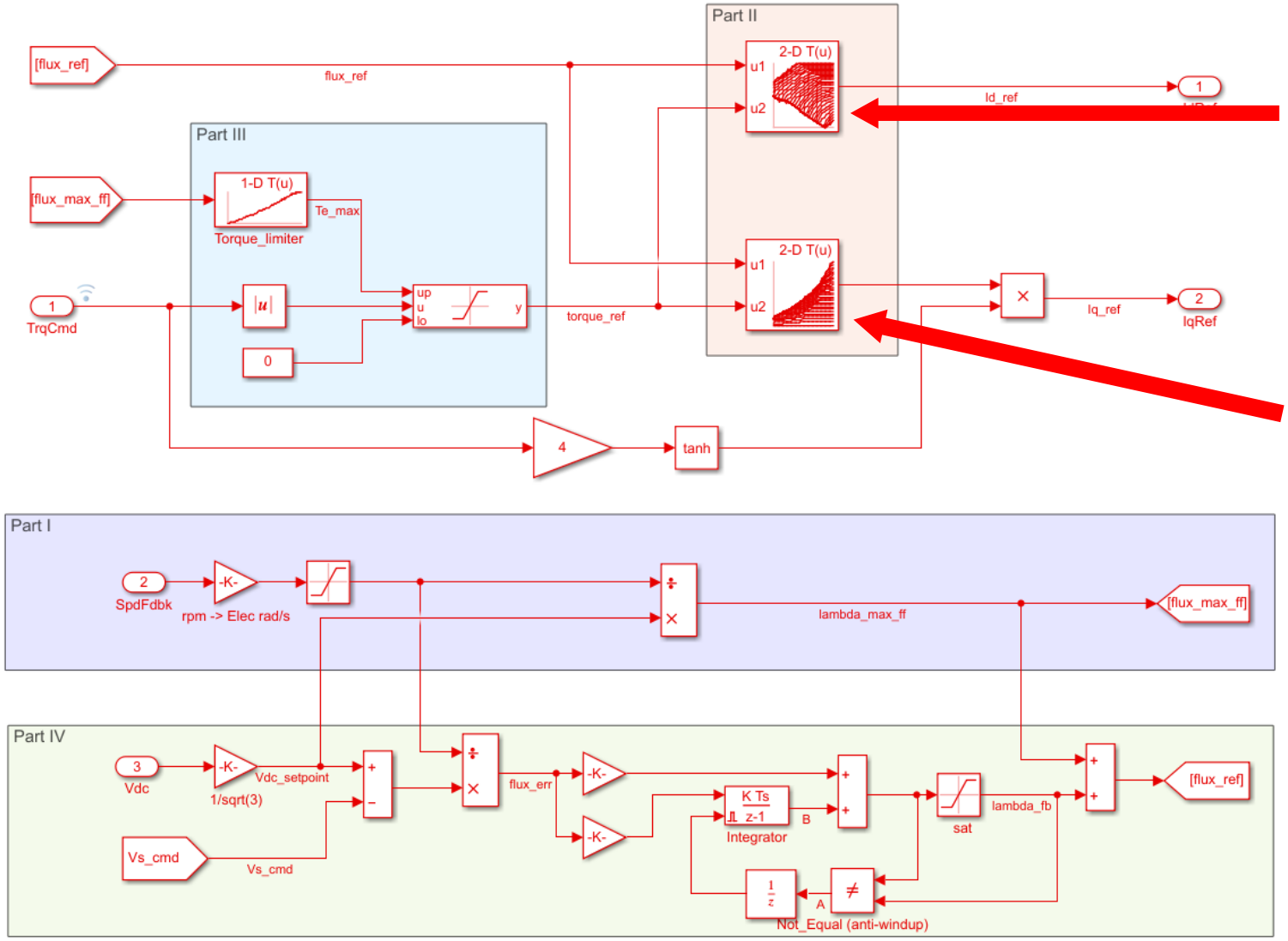
# Calibration Results – Fill Calibration Tables

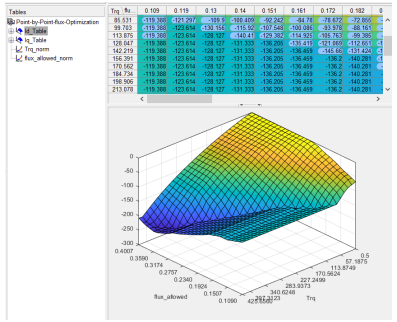


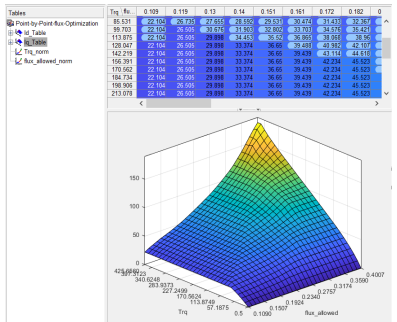

$i_d$ table




$i_q$ table


Part II
[flux_ref]
flux_ref
2-D T(u)
u1
u2
Id_ref
1
Part III
[flux_max_ff]
1-D T(u)
Te_max
Torque_limiter
1
TrqCmd
|u|
up
u
lo
y
0
torque_ref
2-D T(u)
u1
u2
Iq_ref
2
IqRef
4
tanh
Part I
2
SpdFdbk
-K-
rpm -> Elec rad/s
lambda_max_ff
[flux_max_ff]
Part IV
3
Vdc
-K-
1/sqrt(3)
Vdc_setpoint
Vs_cmd
Vs_cmd
flux_err
-K-
-K-
K Ts
z-1
Integrator
B
sat
lambda_fb
[flux_ref]
A
Not_Equal (anti-windup)





# Takeaways

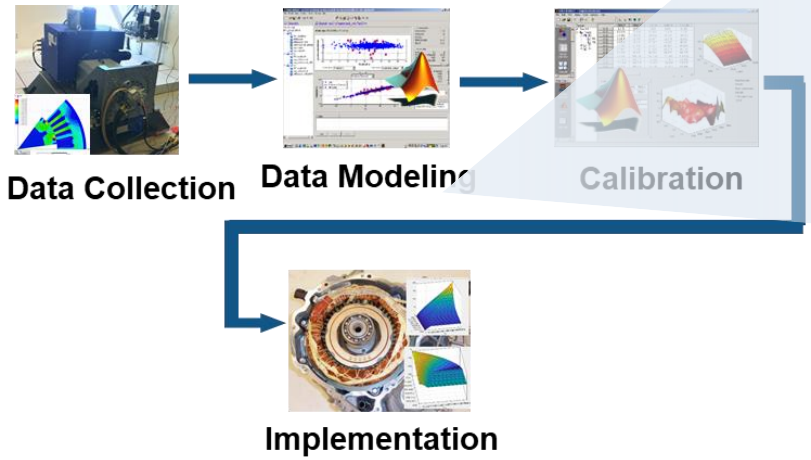
## Model-based calibration workflow

- PMSM control calibration → optimization problem
- Automated calibration process
- Robust to different PMSM designs

| Manual | Model-Based Calibration |
|---|---|
| Rule-based searching method - | Optimization + |
| Requires lots of scripting - | Automated + |
| Error prone - | Robust + |

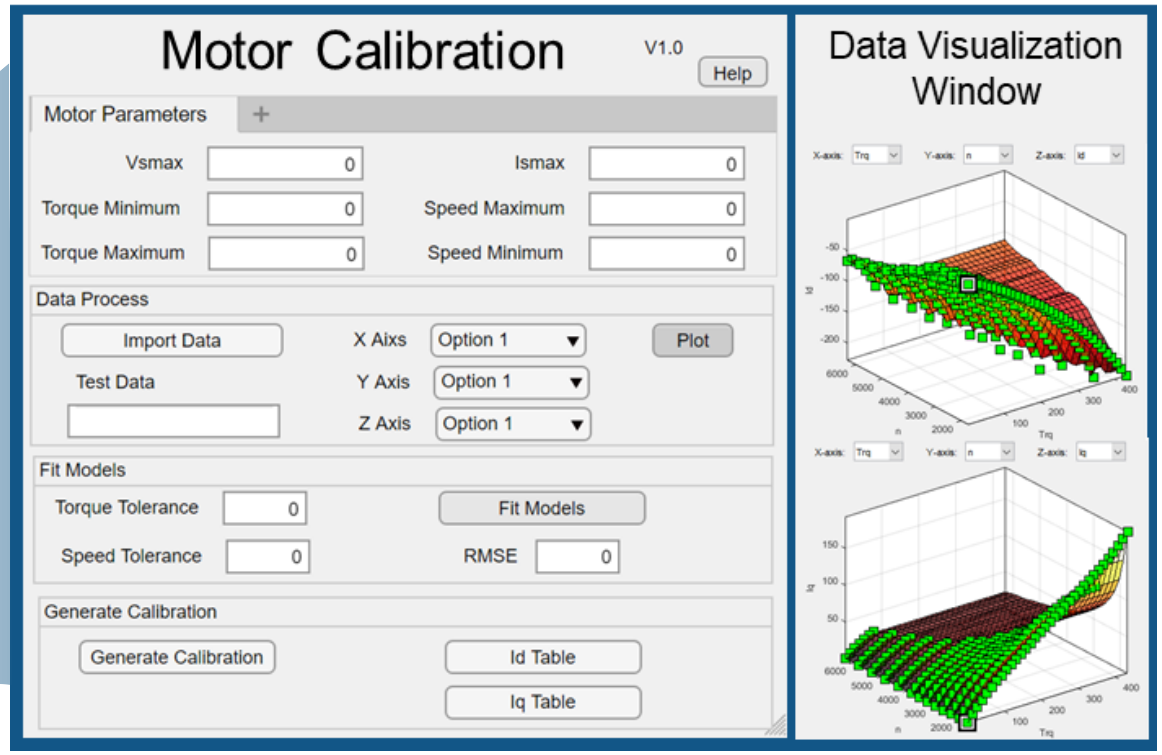
# PMSM Calibration Consulting Service

- Service components
  - Hands on calibration support
    - Workflow discussion
    - Coaching of MBC calibration method
  - Calibration workflow tool
    - GUI that implements the entire MBC workflow




Calibration Workflow

Visualization



# Contacts

dakaihu@mathworks.com

jgazzarr@mathworks.com