MATLAB EXPO

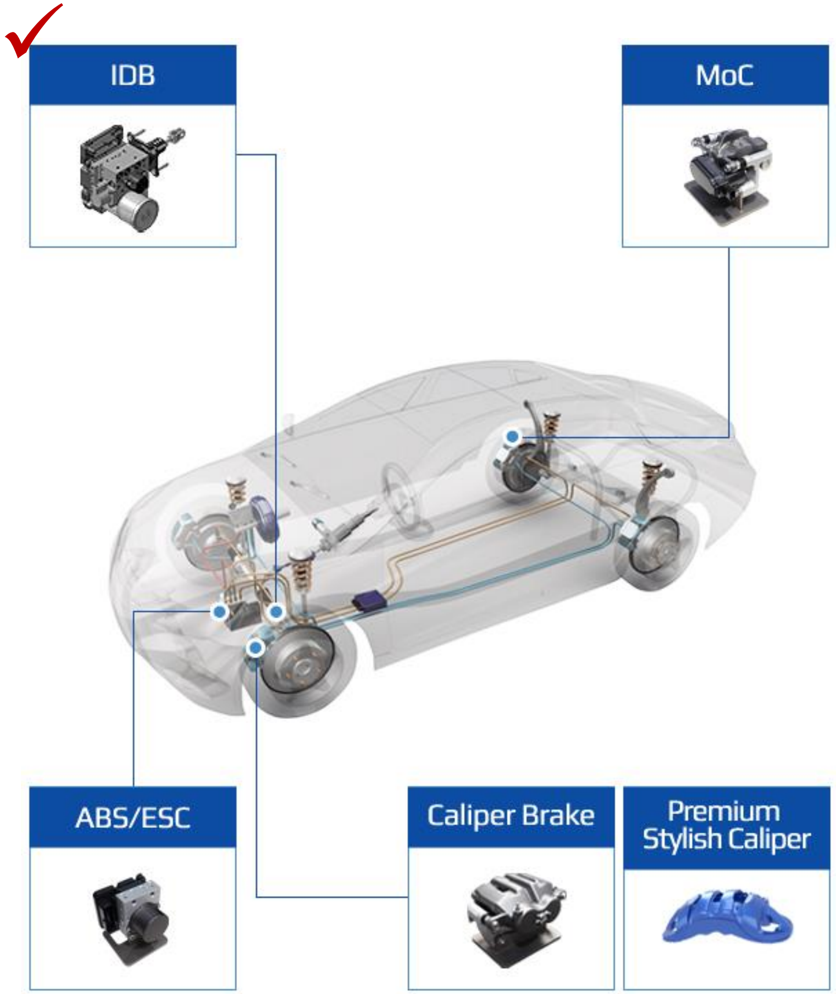
# Motor Parametric Design Using an Electro-Hydraulic Model of a Brake System

*SeonYeol Oh, HL MANDO*

MathWorks®

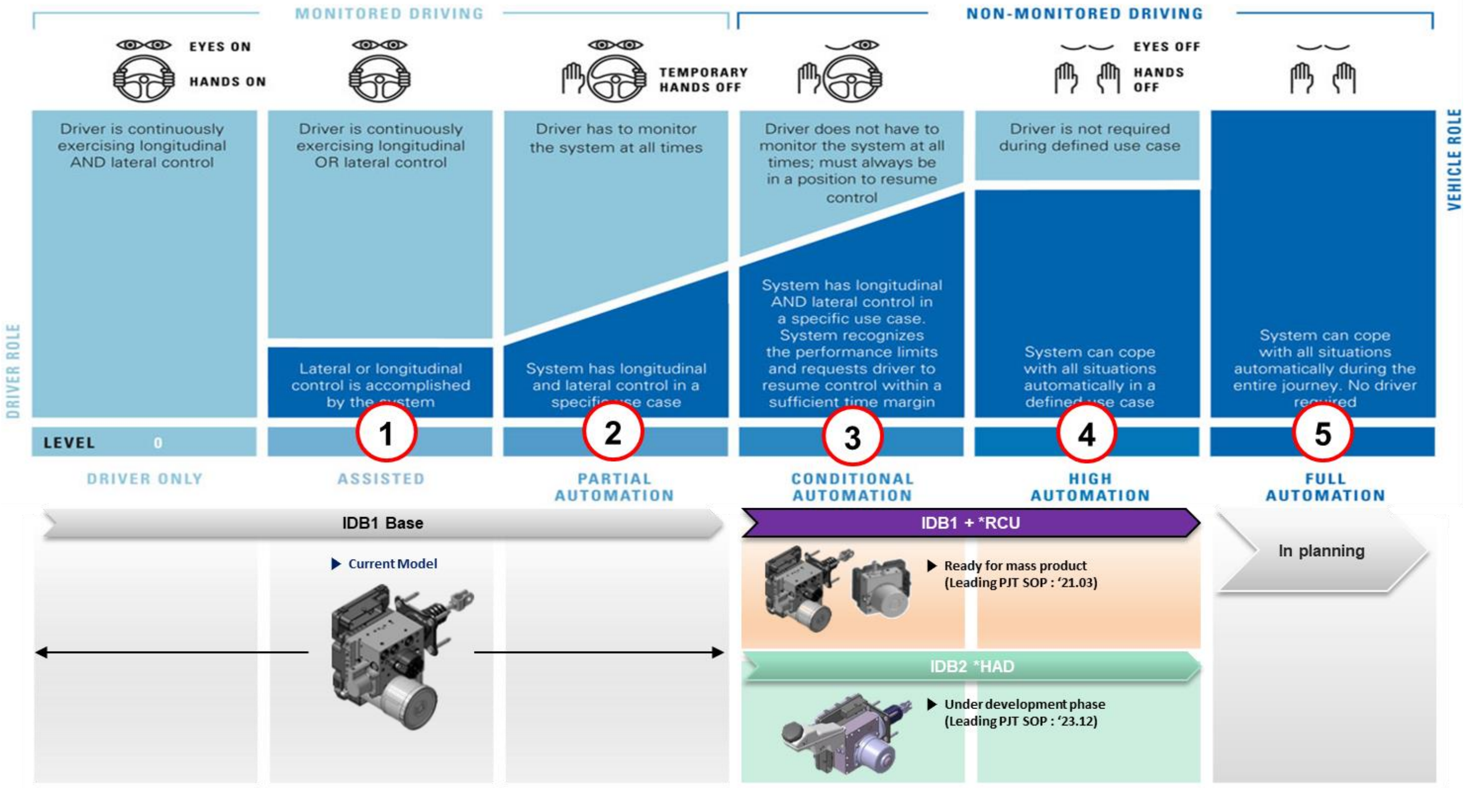
# Contents

# HL MANDO – Brake BU



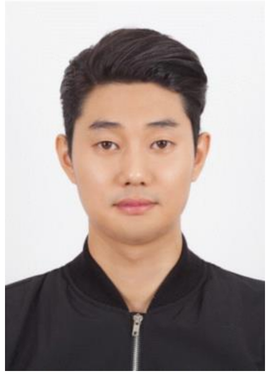

## Autonomous Driving Strategy – *Mando Solution*

- **Mando Autonomous Driving Development Strategy for each Level**




*RCU : Redundancy Control Unit / *HAD : Highly Automated Driving

# 발표자 소개



오선열 책임연구원

HL 만도 / Brake BU

- 연구 분야
  - MPS/PTS Sensor & Magnet 설계 및 전자기 성능 검증 (MAXWELL)
  - 1D 기반 모터 시스템 구현 및 검증 (SIMULINK/AMESim)
  - 제동 모터 전자기 성능 & 구조/진동 특성 검토 (MAXWELL/ABAQUS)

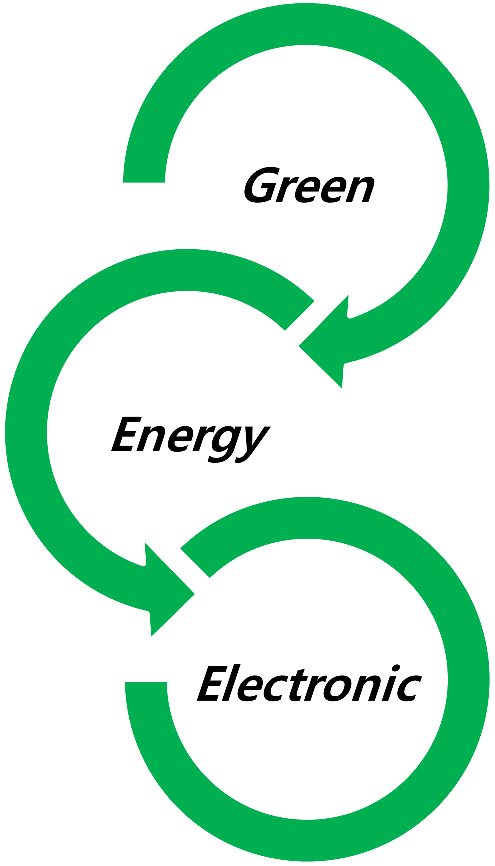
- 학력
  - 고려대학교 기계공학과 학사
  - 고려대학교 기계공학과 석사

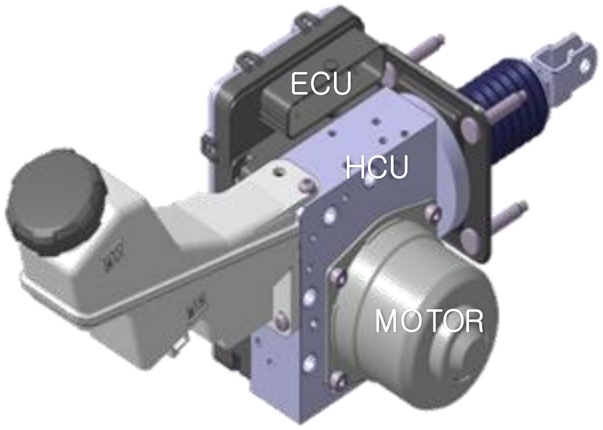
- 경력
  - 고려대학교 기계공학과 정밀기술연구실 (2012~2014)
  - 2020 HL Global R&D Conference 논문 우수상(2020, HL 만도)
  - 2022 HL Global R&D Conference 논문 대상(2022, HL 만도)
  - HL 만도 Global R&D Center 책임연구원 (2014 ~ 현재)

# Contents

# Background (IDB)

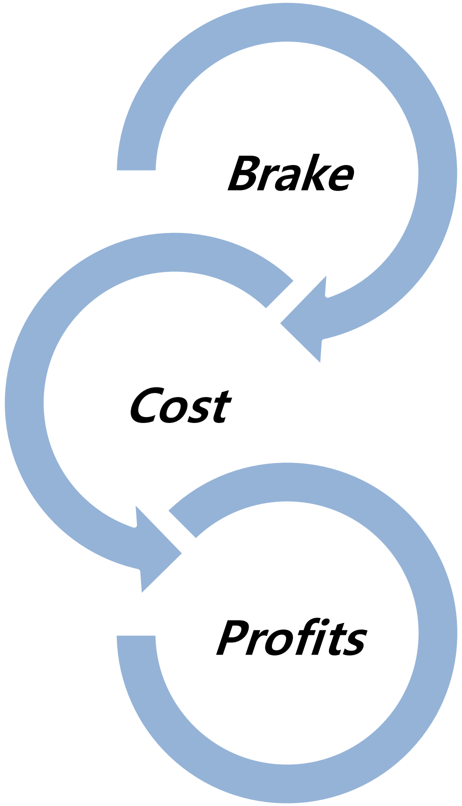
**Market (Environment)**



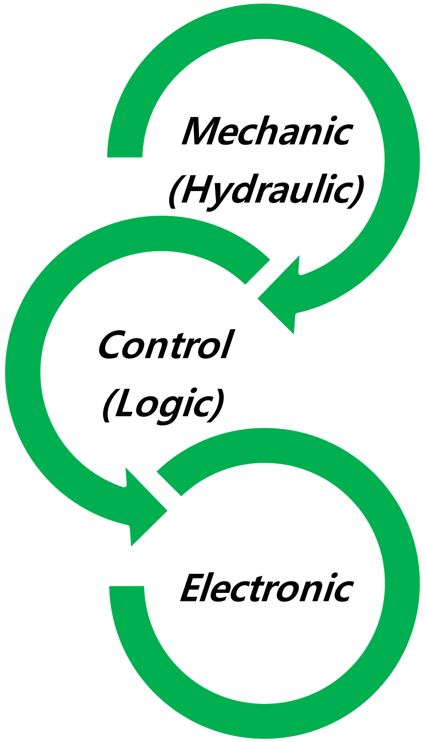

- **Electronic Brake System (IDB)**

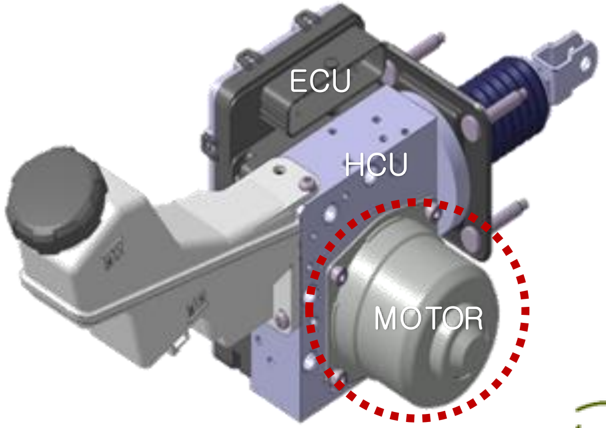
**Company(Sales)**



# Background & Purpose (Motor)

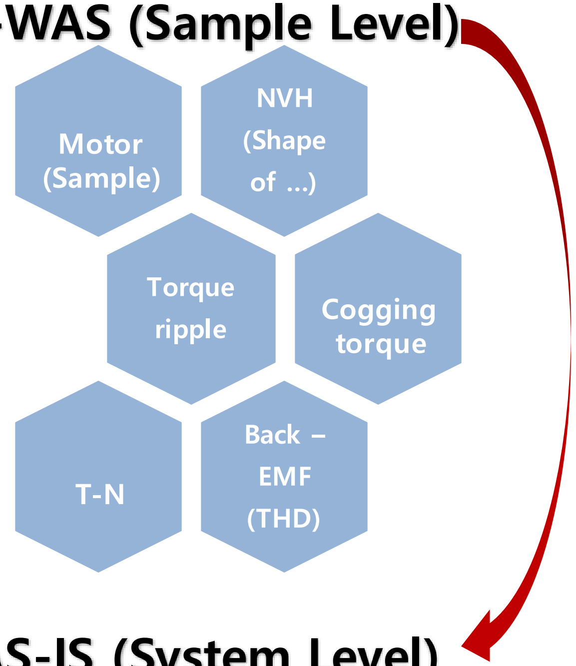
## ✓ Integrated & Complex



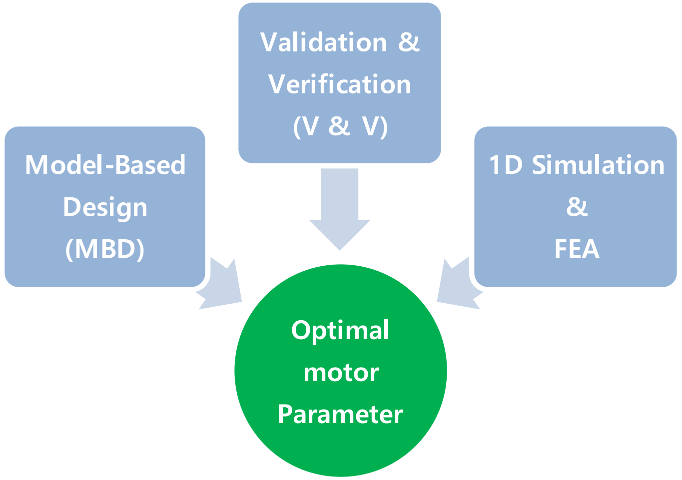




How to design motor ?

## ✓ AS-WAS (Sample Level)




## ✓ AS-IS (System Level)



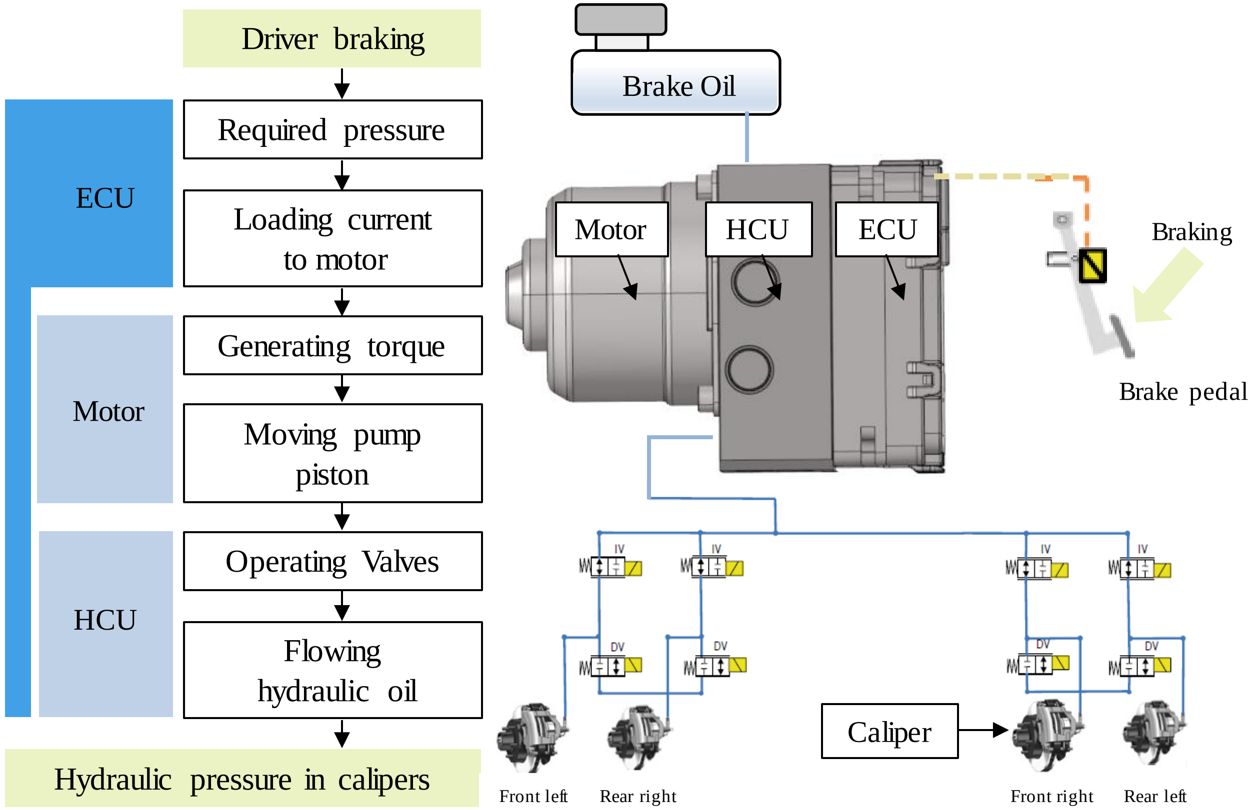

➢ **Comment(of IEEE & Mando reviewer)**

Trend & Creativity

Sound(logical)

Contribute to Work or Knowledge

# Background - IDB System’s Principle



# Contents

# Why use MBD in IDB Motor Design?

## Challenge

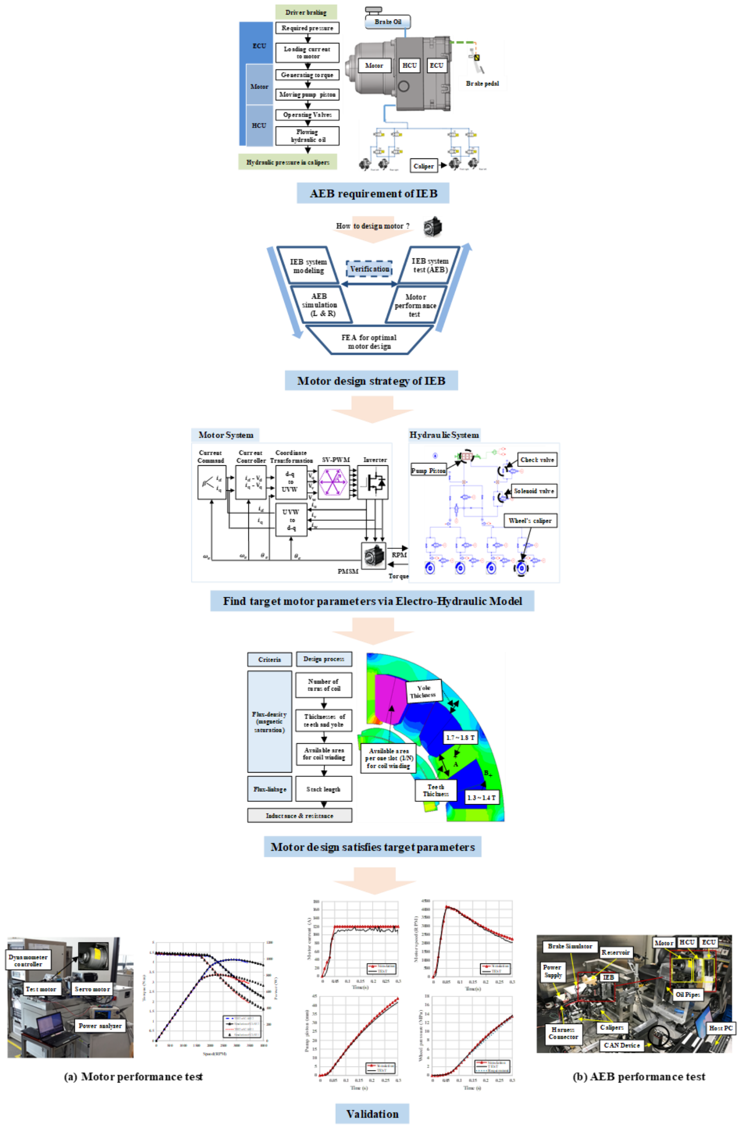
- Need to design an optimal motor to meet OEM’s requirements for Autonomous Emergency Braking(AEB)’s performance

## Solution

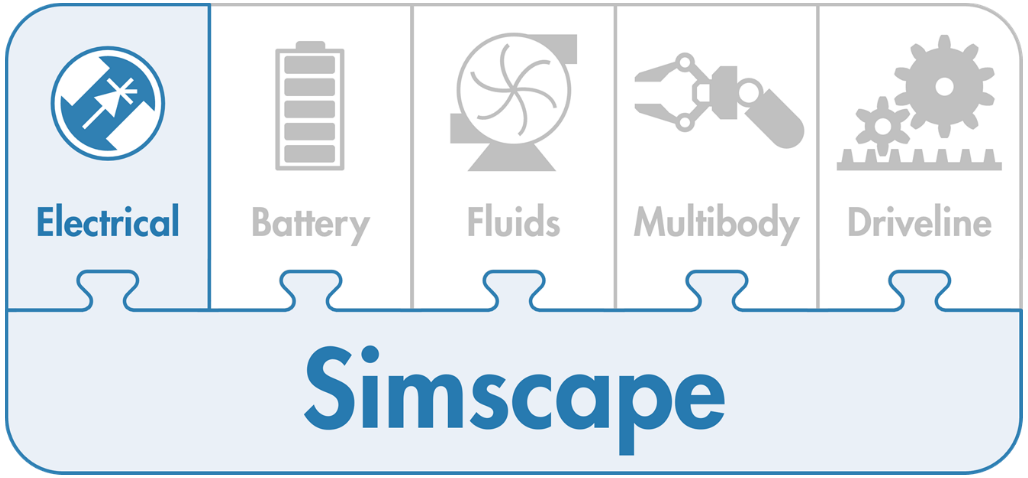
- Use *Simscape* to build a motor model and find the optimal motor parameter

## Results

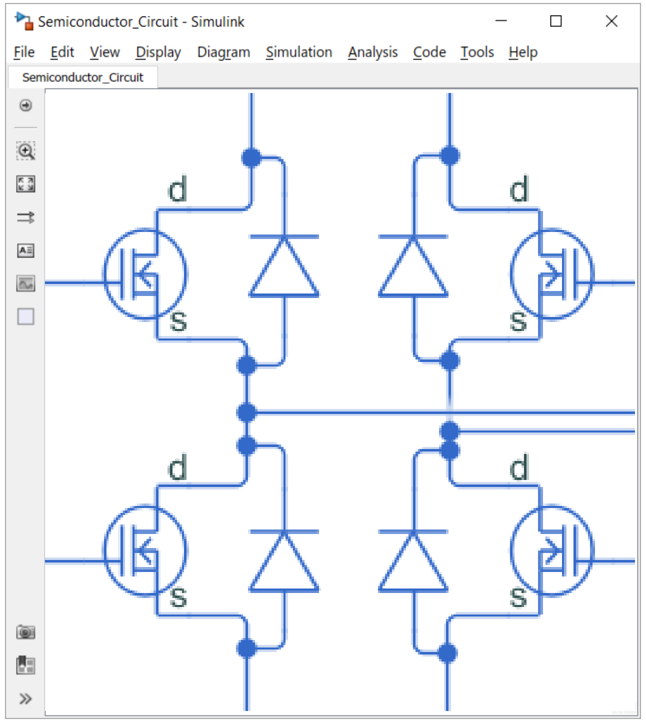
- Motor designed at the system level throughout Model-Based Design(MBD)
- Efficiency improved for designing a motor in a brake system
- OEM’s requirements and standards met

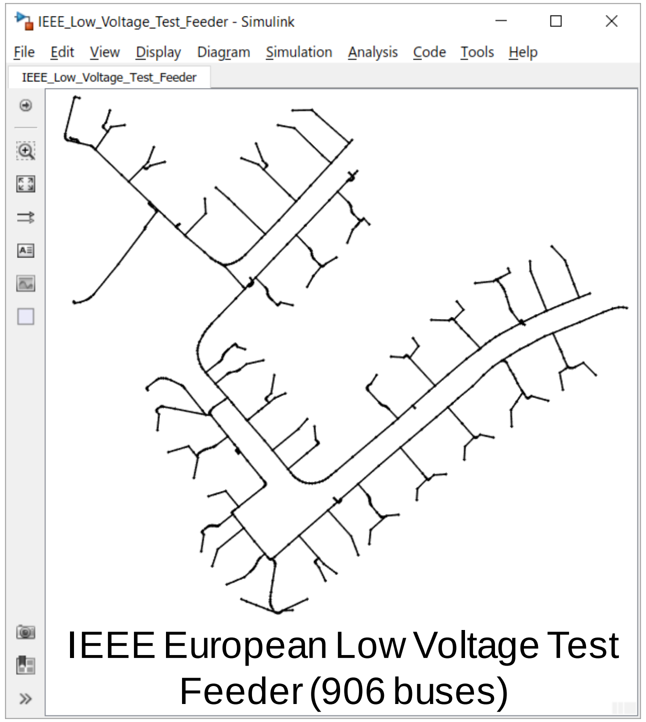


# Simscape Electrical




- Enables physical modeling (acausal) of electronic, mechatronic, and electrical power systems
  - Electrical system topology represented by schematic circuit
- With Simscape Electrical you can
  - Evaluate analog circuit architectures
  - Develop mechatronic systems with electric drives
  - Analyze the generation, conversion, transmission, and consumption of electrical power at the grid level

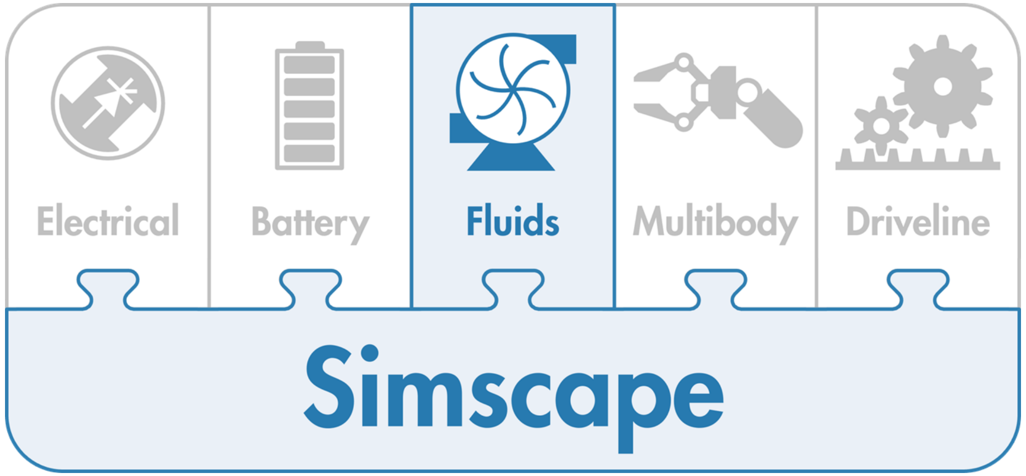


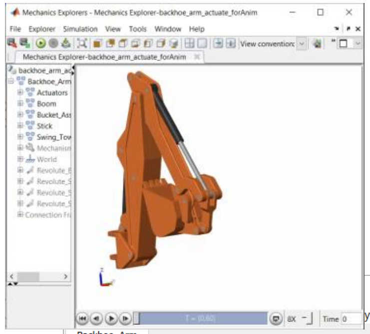



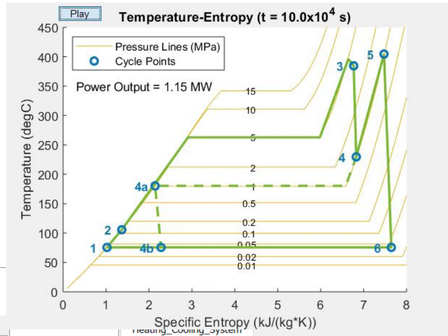
# Simscape Fluids

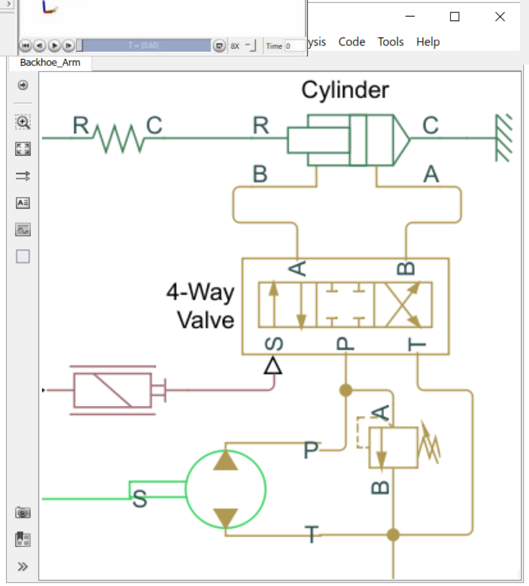
- Enables physical modeling (acausal) of fluid systems
  - Fluid power, heating, cooling, and fluid transportation
  - Liquids, gases, and multiphase fluids

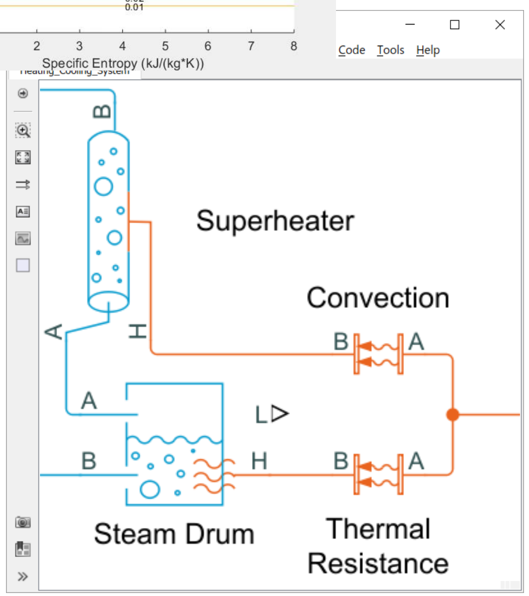
- With Simscape Fluids you can
  - Refine requirements for fluid systems
  - Discover integration issues early
  - Design control algorithms and logic within the Simulink environment
  - Test embedded software without hardware prototypes



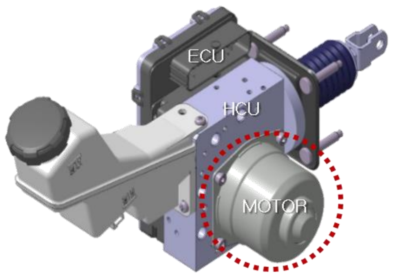


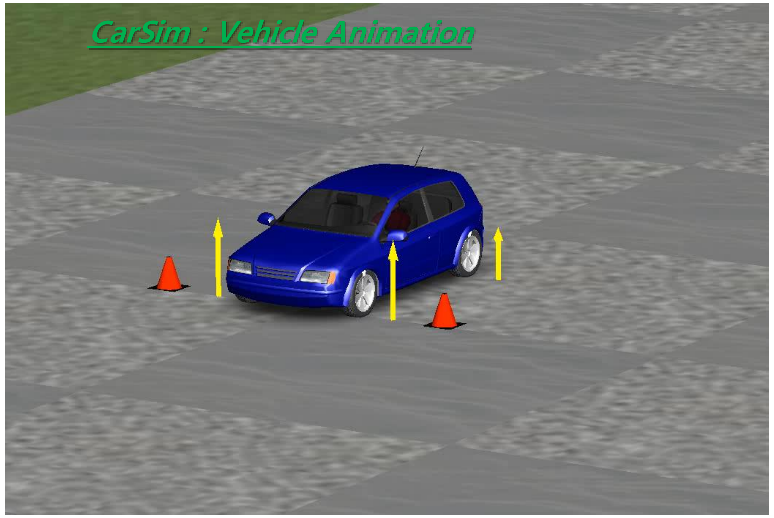



# Motor Design Process with MBD

- Brake Max. Performance Requirement (System)
  - ① Max. Pressure → Steady-State ✓
  - ② Autonomous Emergency Braking(AEB) → Transient



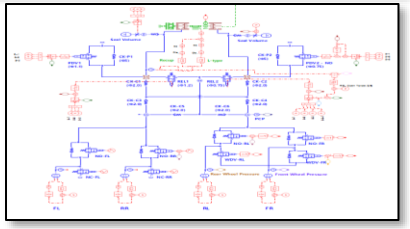

How to design motor ?



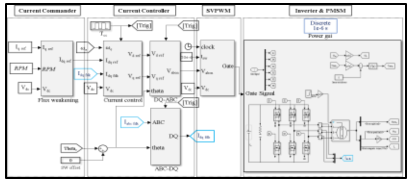

**Step 1 : System Level**

**1D Hydraulic + Motor Model Simulation**

유압 시스템



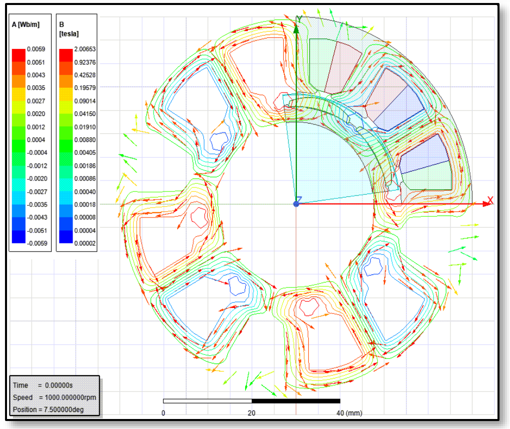
모터 시스템



**Step 2 : Motor Sample Level(Detail)**

**Finite Element Analysis**

F E A



# Motor Design Process with MBD

## Modeling & Simulation

IDB
system modeling

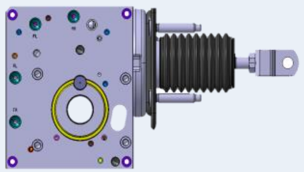
AEB Simulation

FEA for optimal
motor design

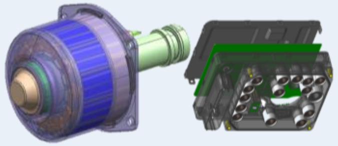
## Verification

Motor 성능 시험

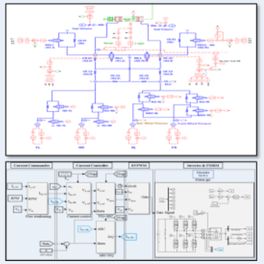
IDB System
시험(AEB)



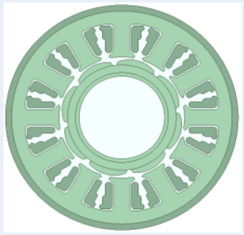
Hydraulic System 모델 구성



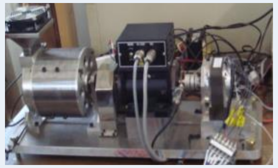
Motor System 모델 구성



AEB Simulation



유한 요소 해석



모터 성능 시험

IDB 응답 성능 시험

# Motor Design Parameter

## Motor Voltage Equation
(Current Controller)

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega L_q i_q$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \varphi_m$$

## Motor(SPM)

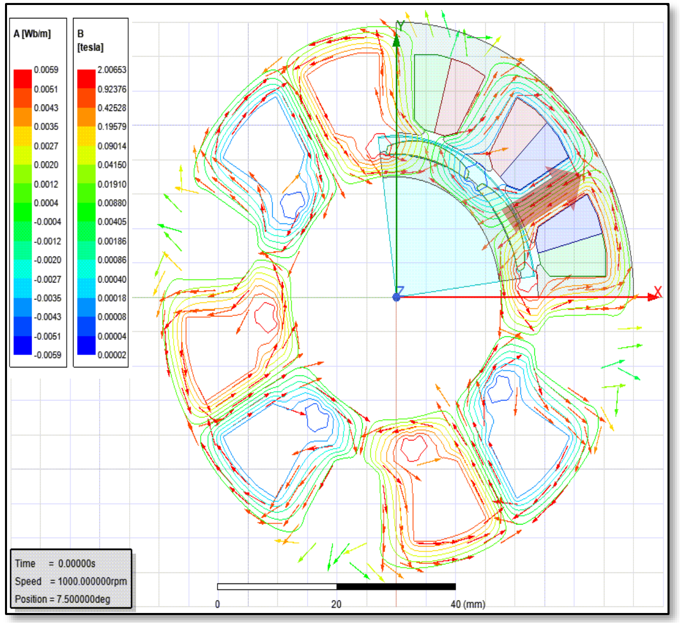
Torque ∝ Current

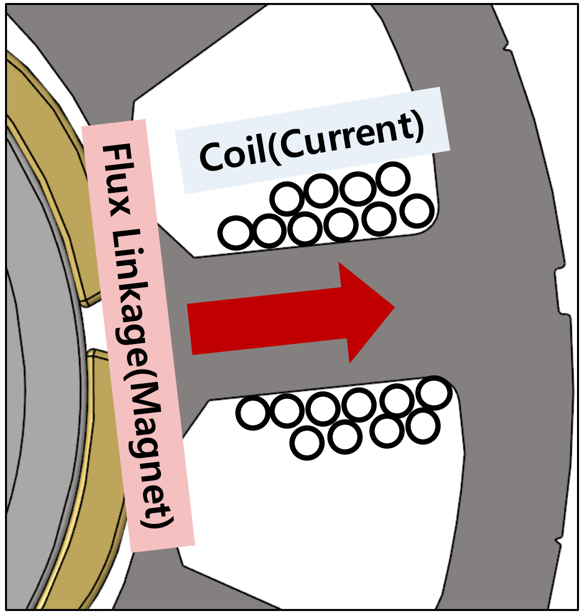
$$T_e = \frac{3}{2} P_n \varphi_m i_q$$

✓R (Coil Resistance), ✓L (Coil Inductance), $\varphi$ (Flux Linkage)

(System Response Performance ○, NVH △)

# Motor Design Parameter(Flux Linkage)




**Motor(SPM)**

**Torque ∝ Flux**

$$T_e = \frac{3}{2} P_n \varphi_m i_q$$

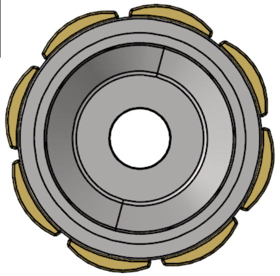
**Coil Current & Flux Linkage**
**→ Motor Torque**

# Motor Design Parameter(Flux Linkage)

- Brake Max. Performance Requirement (System)
① Max. Pressure → Steady-State

**Max. Torque & # of Poles**
$T_e, P_n$

**Max. Pressure, Pump Size, Rotor & # of Magnet Poles**

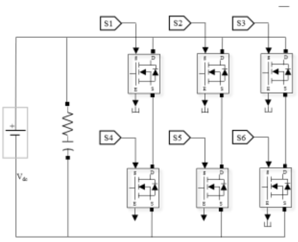


**Motor(SPM) Torque**

$$T_e = \frac{3}{2} P_n \varphi_m i_q$$

**Max. Current**
$i_q$

**Inverter Design**

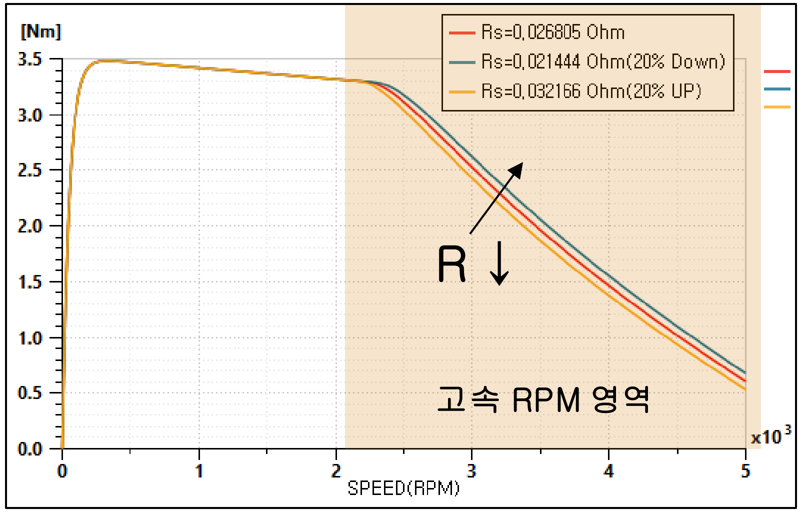


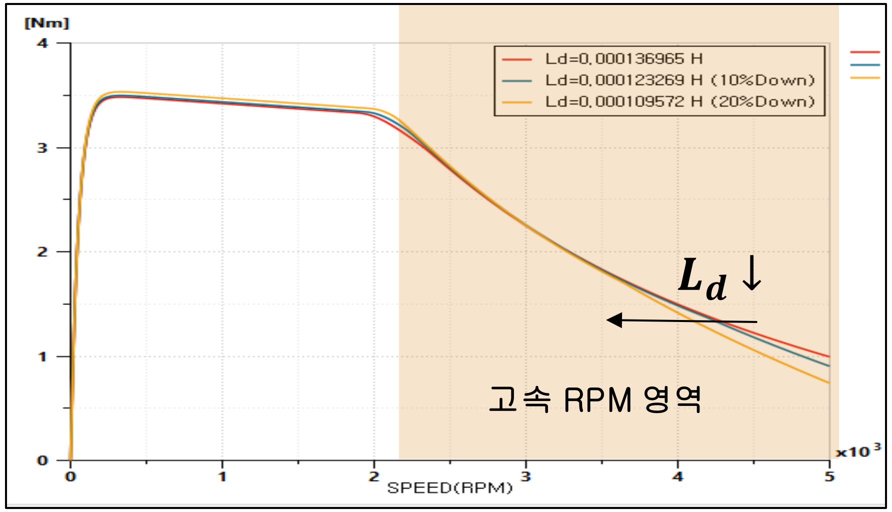
**$\varphi$ (Flux Linkage) decision**

# Motor Design Parameter (Coil Resistance & Inductance)

- Brake Max. Performance Requirement (System)
  ② Autonomous Emergency Braking(AEB) → Transient

토크 & 속도 선도



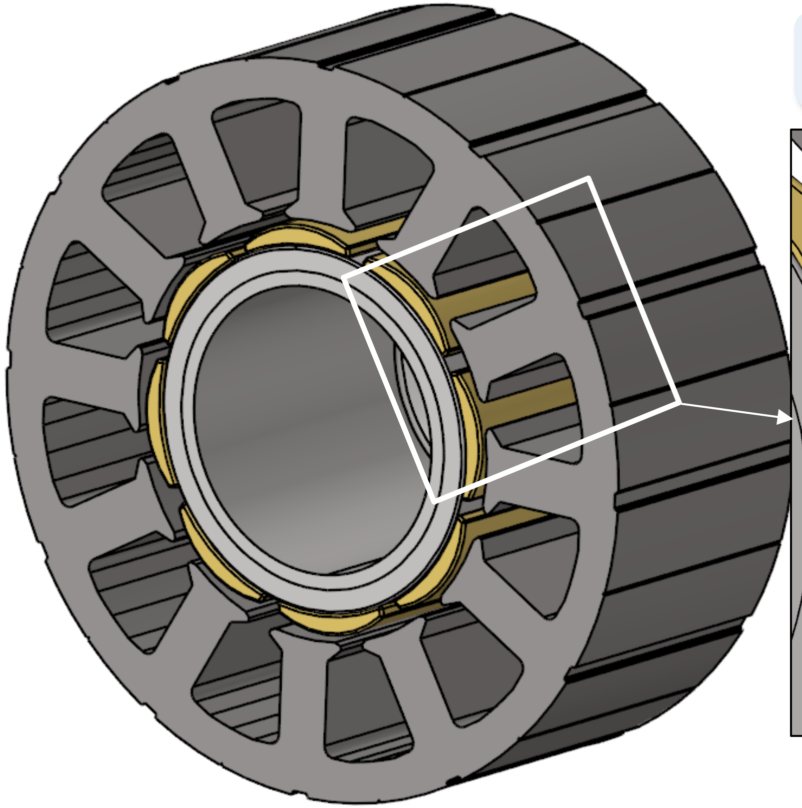




R (Coil Resistance), L (Coil Inductance)

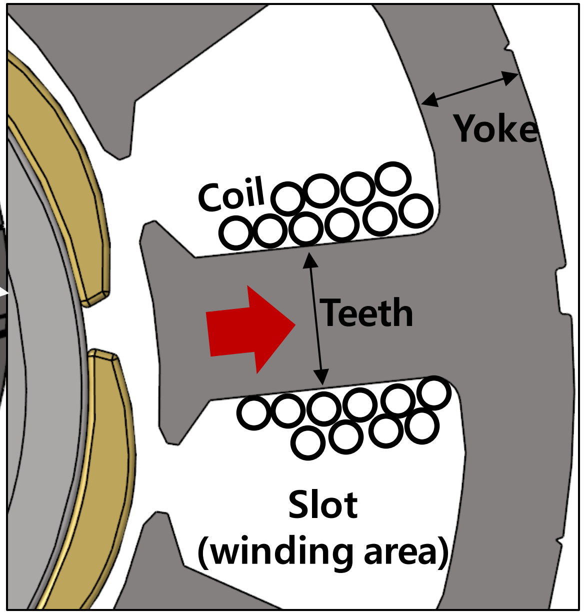
⇩

1D System Model is needed for R, L decision

# Motor Design Parameter (Coil Resistance & Inductance)

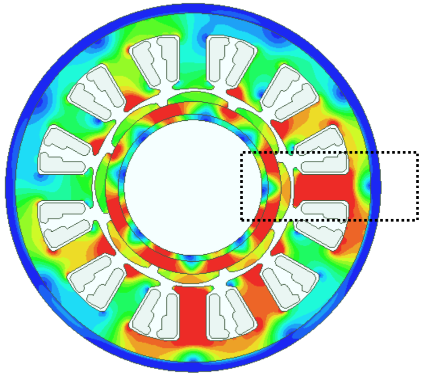


Motor's Number of Coil Turns(N)




R (Coil Resistance) ∝ N

L (Coil Inductance) ∝ $N^2$



Number of Turns (N) ↑ → Teeth & Yoke ↑(Saturation X) → Shortage of winding area

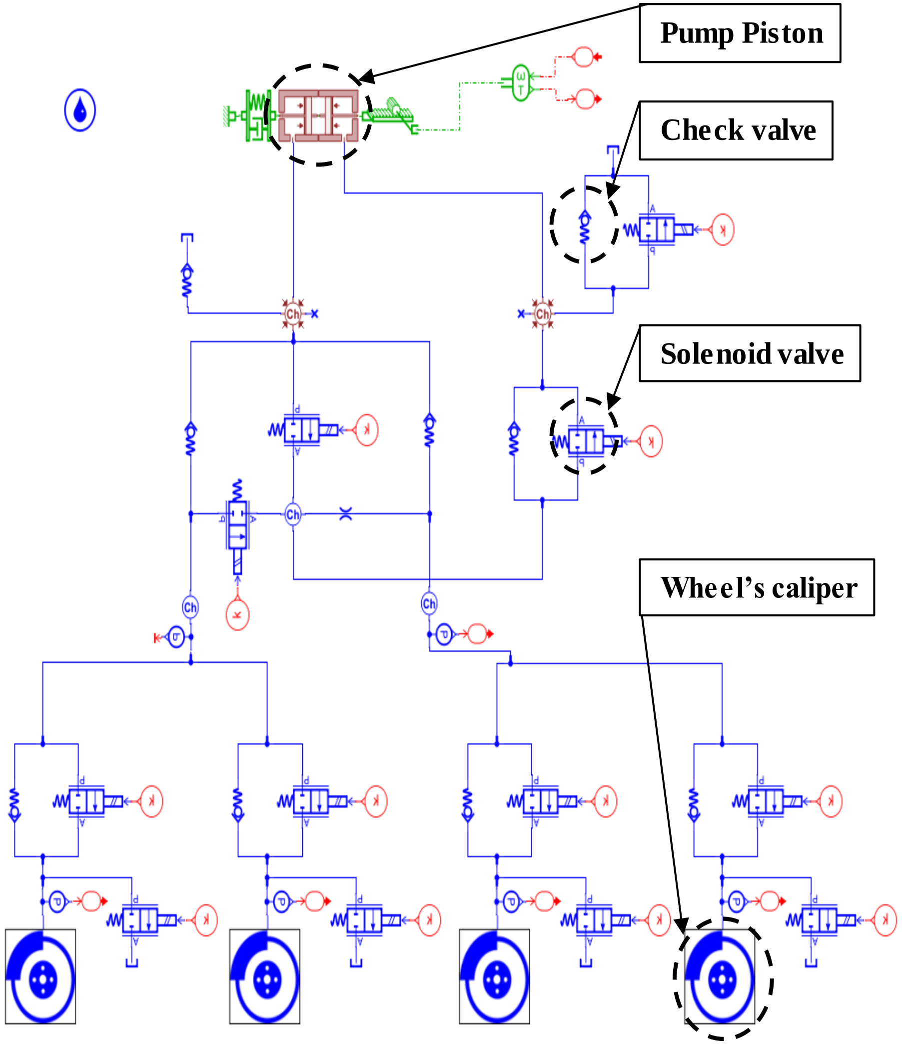
⇩

Finite Element Analysis (FEA) is needed for optimal detail design

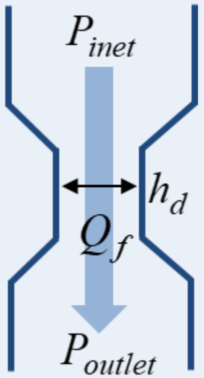
# Contents

# System Modeling

➤ **Hydraulic System (AMESim+CFD)**

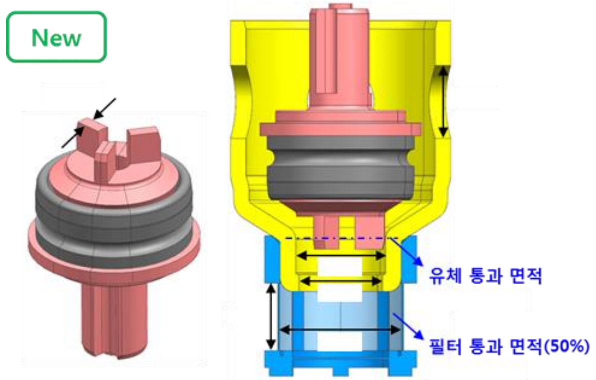



<Hydraulic System (simple) >

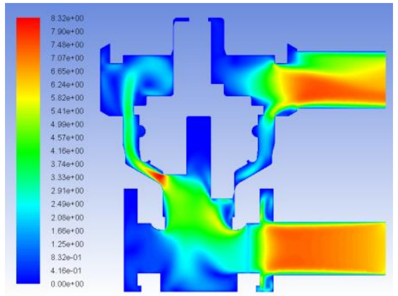



$$Q_f = c_q \sqrt{\frac{2\Delta P}{\rho}} A_c$$

$$c_q = c_{q\,max} \tanh\left(\frac{2\lambda}{\lambda_{crit}}\right)$$



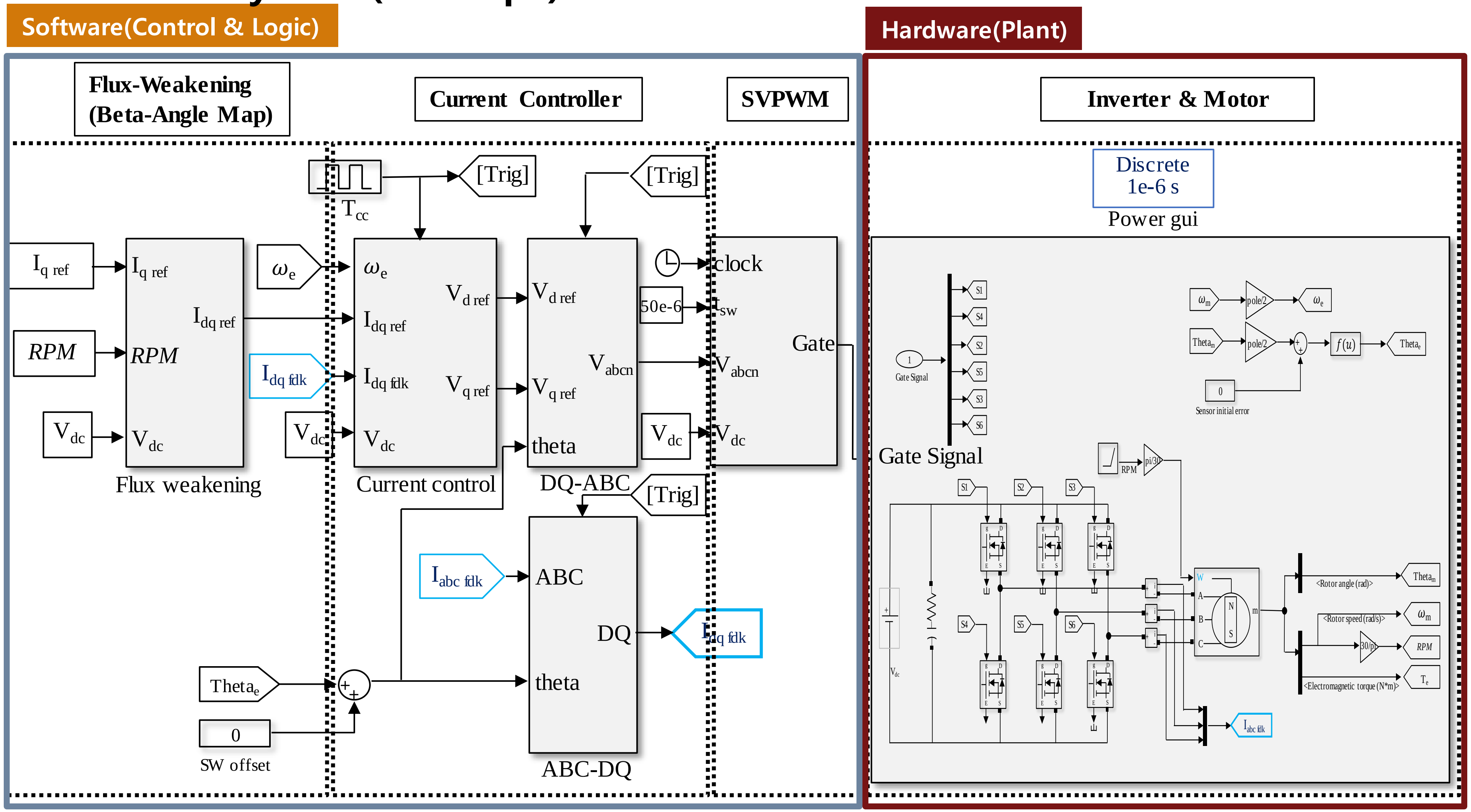

| Pressure Drop [bar] | Flow Rate [cc/s] | Flow Coefficient @Φ4.3 |
|---|---|---|
| 0.214 | 40.3 | 0.43 |
| 0.419 | 61.4 | 0.47 |
| 0.825 | 91.8 | 0.5 |
| 1.03 | 104.1 | 0.51 |



< CFD Analysis>

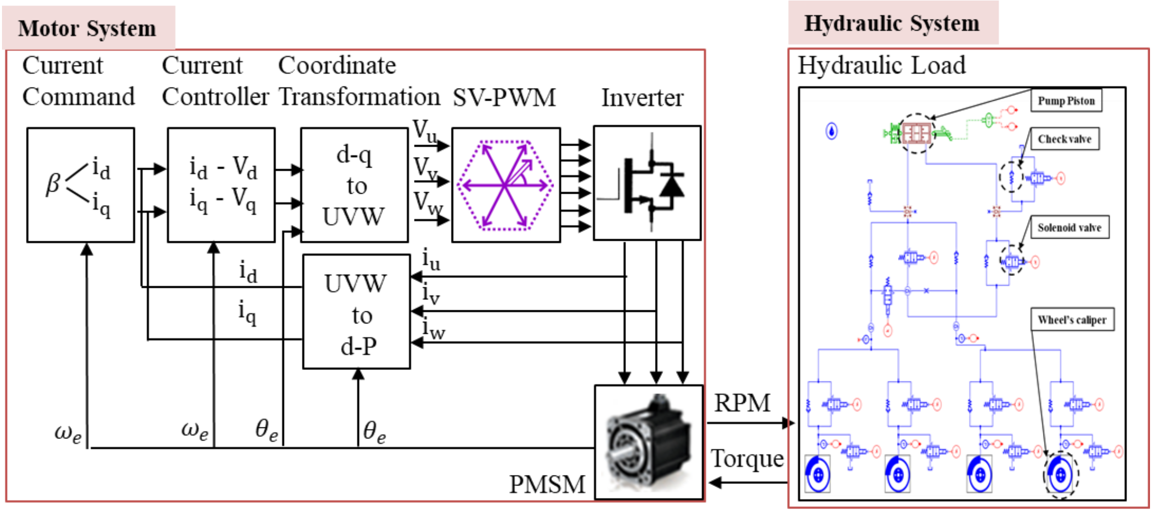
# System Modeling

➢ **Motor System (Simscape)**




<Motor System>

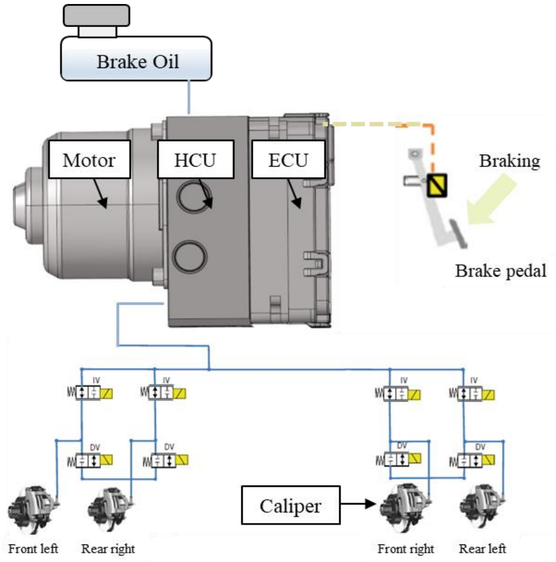
# Hydraulic + Motor System Model Simulation (AEB)




**Autonomous Emergency Braking(AEB) Simulation**

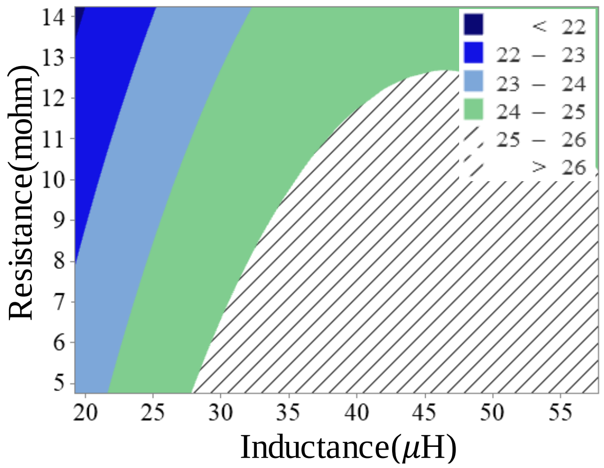
**Ford Need**

| | Wheel Pressure Range | build-up rate (Requirement) |
|---|---|---|
| ① | 0 → 2.5 MPa (from 0 MPa to 2.5 MPa) | 25 MPa/s |
| ② | 0 → 5 MPa (from 0 MPa to 5 MPa) | 35 MPa/s |
| ③ | 0 → 10 MPa (from 0 MPa to 10 MPa) | 42.5 MPa/s |
| ④ | 0 → 14 MPa (from 0 MPa to 14 MPa) | 45 MPa/s |

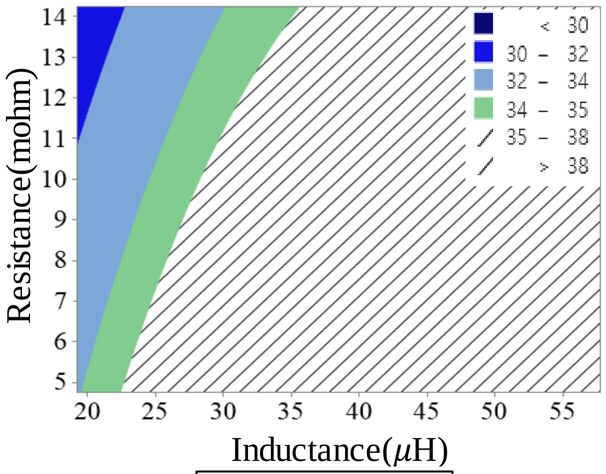


# AEB Simulation Result (Parameter Study(R,L))

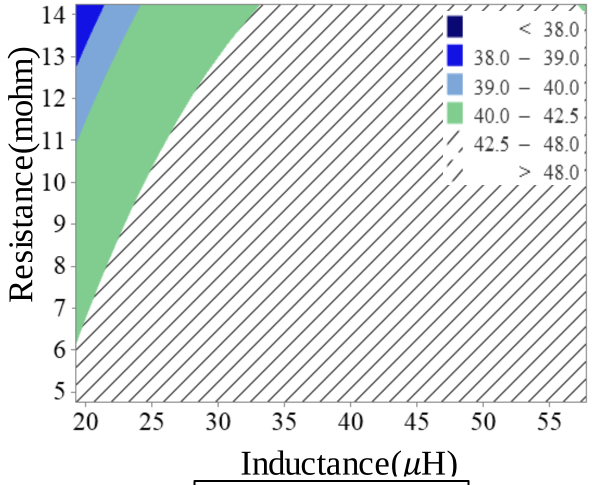
: Section that meets the pressure build-up rate requirements.



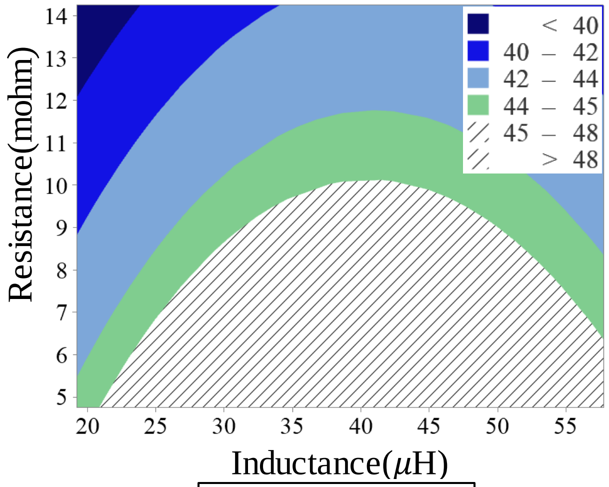

① 0 → 2.5 MPa



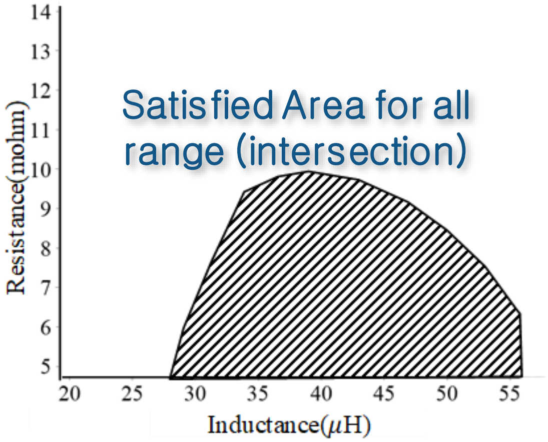

② 0 → 5 MPa




③ 0 → 10 MPa



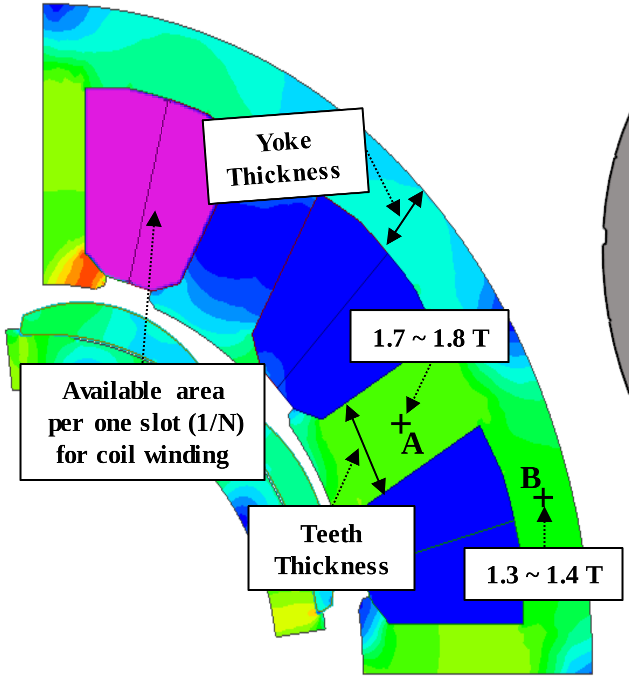

④ 0 → 14 MPa

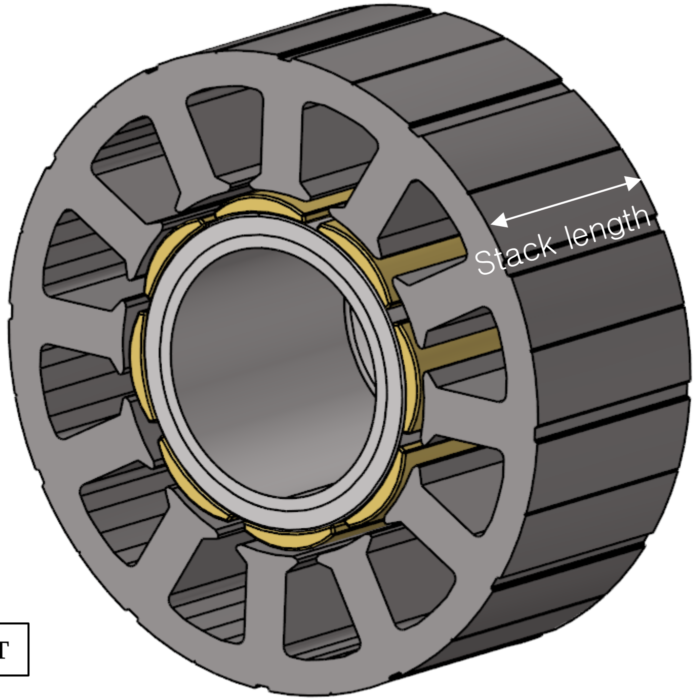



Resistance : The lower, the better
Inductance : Deflection occurs for each range

# Motor Detail Design (FEA)

| Criteria | Design process |
|---|---|
| Flux-density (magnetic saturation) | Number of turns of coil ↓ |
| | Thicknesses of teeth and yoke ↓ |
| | Available area for coil winding ↓ |
| Flux-linkage | Stack length ↓ |
| Inductance & resistance | |



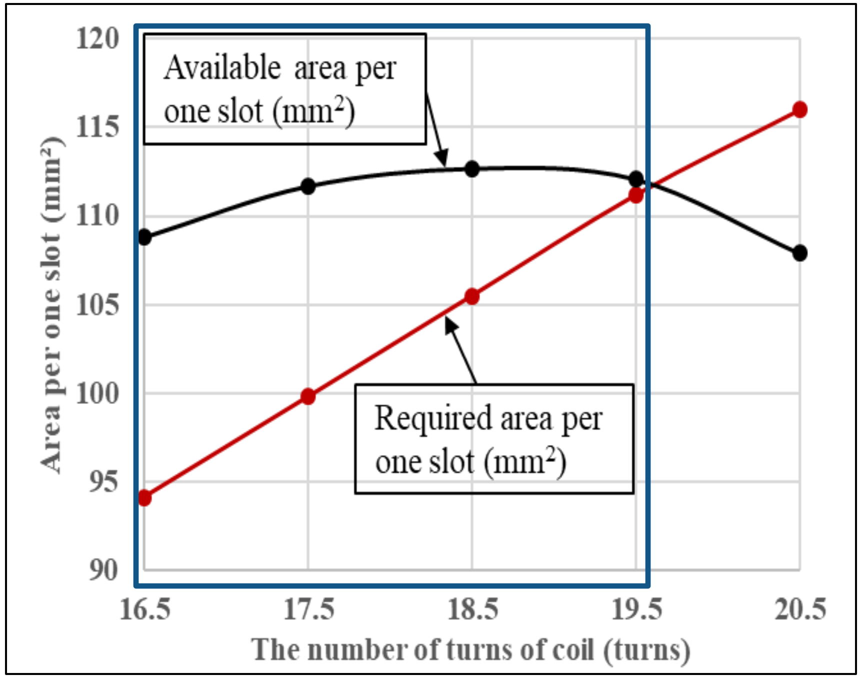




❖ Stator diameter is determined by packaging limit

# Motor Detail Design Result (FEA)

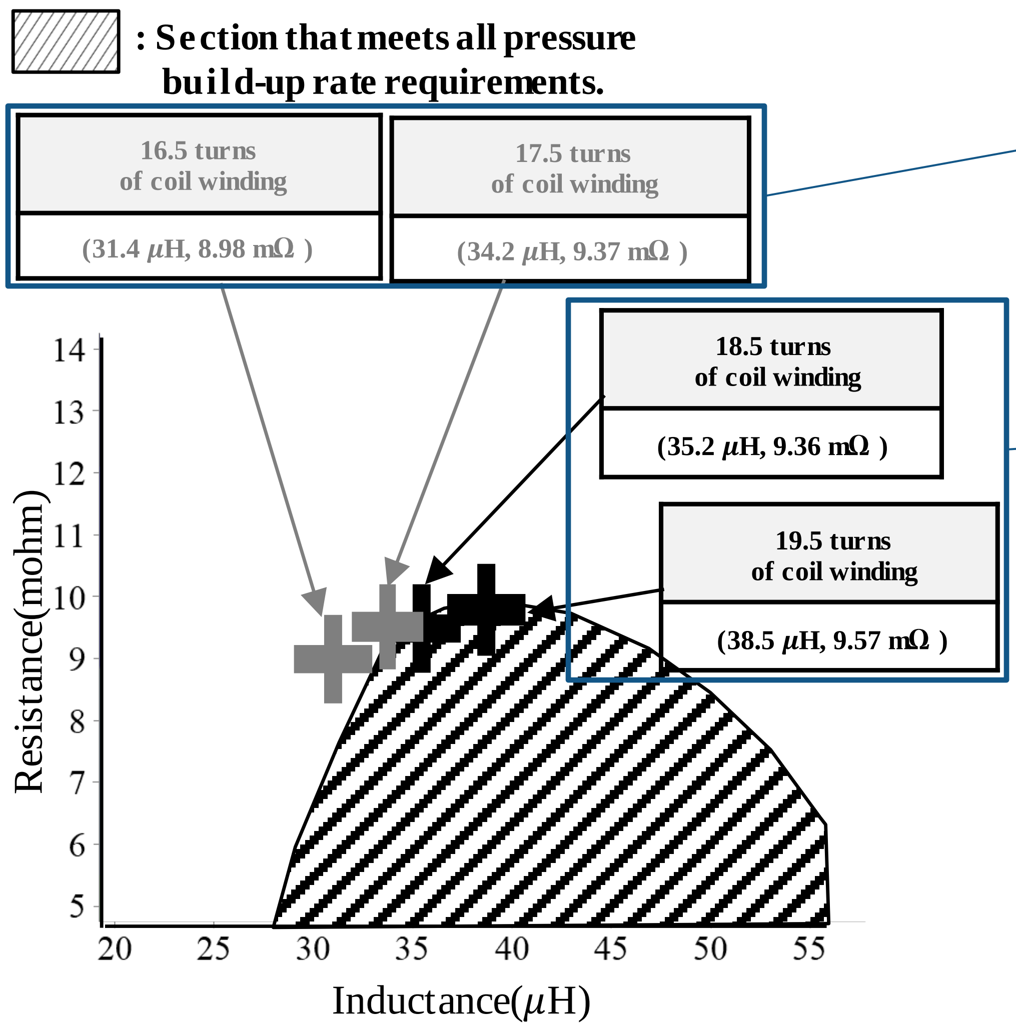
| Coil Turns(N) | 16.5 | 17.5 | 18.5 | 19.5 | 20.5 |
|---|---|---|---|---|---|
| Required area for coil winding ($mm^2$) | 94.13 | 99.8 | 105.5 | 111.2 | 116.0 |
| Teeth thickness (mm) | 5.9 | 6 | 6.1 | 6.2 | 6.3 |
| Yoke thickness (mm) | 4.35 | 4.4 | 4.5 | 4.6 | 4.7 |
| Available area for coil winding ($mm^2$) | 108.8 | 111.7 | 112.7 | 112.1 | 107.9 |
| Stack length (mm) | 35.7 | 34.2 | 32 | 30.5 | 28.8 |
| Resistance (mΩ) | 8.98 | 9.37 | 9.36 | 9.57 | 9.70 |
| Inductance (µH) | 31.4 | 34.2 | 35.2 | 38.5 | 41.2 |

❖ Coil diameter : 1.25mm, Fill factor : 43%




Coil turns ↑ → required area ↑,
19.5 turns or less required

# Motor Optimal Design (1D System Simulation + FEA Results)




In cases of 16.5 and 17.5, AEB performances are unsatisfied

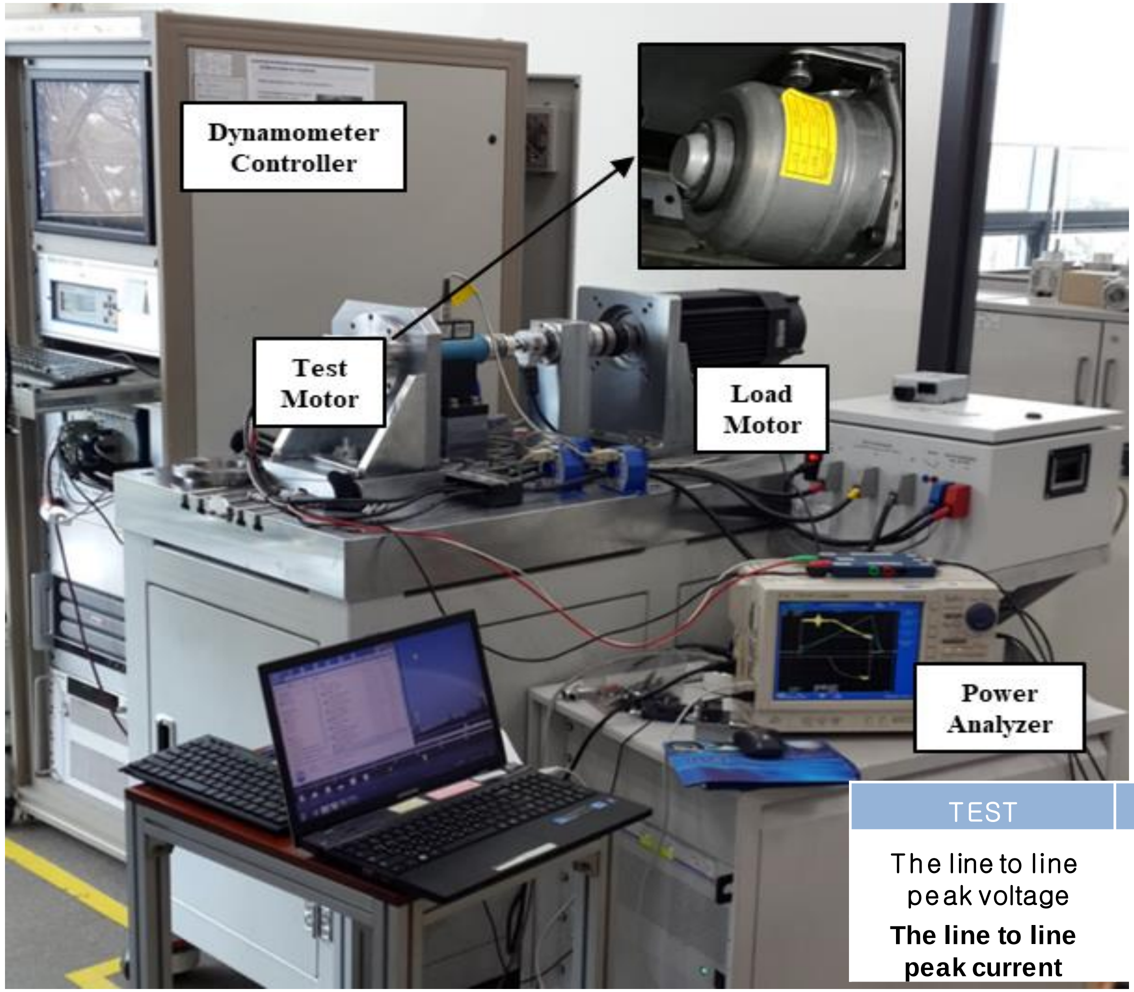
Out of 18.5 and 19.5 turns, excellent results for AEB performance : 19.5 turns

| Parameter | Value |
|---|---|
| Number of coil turns | 19.5 |
| Resistance (mΩ) | 9.57 |
| Inductance (μH) | 38.5 |
| Flux-linkage (Wb) | 0.0064 |

# Contents

# Verification

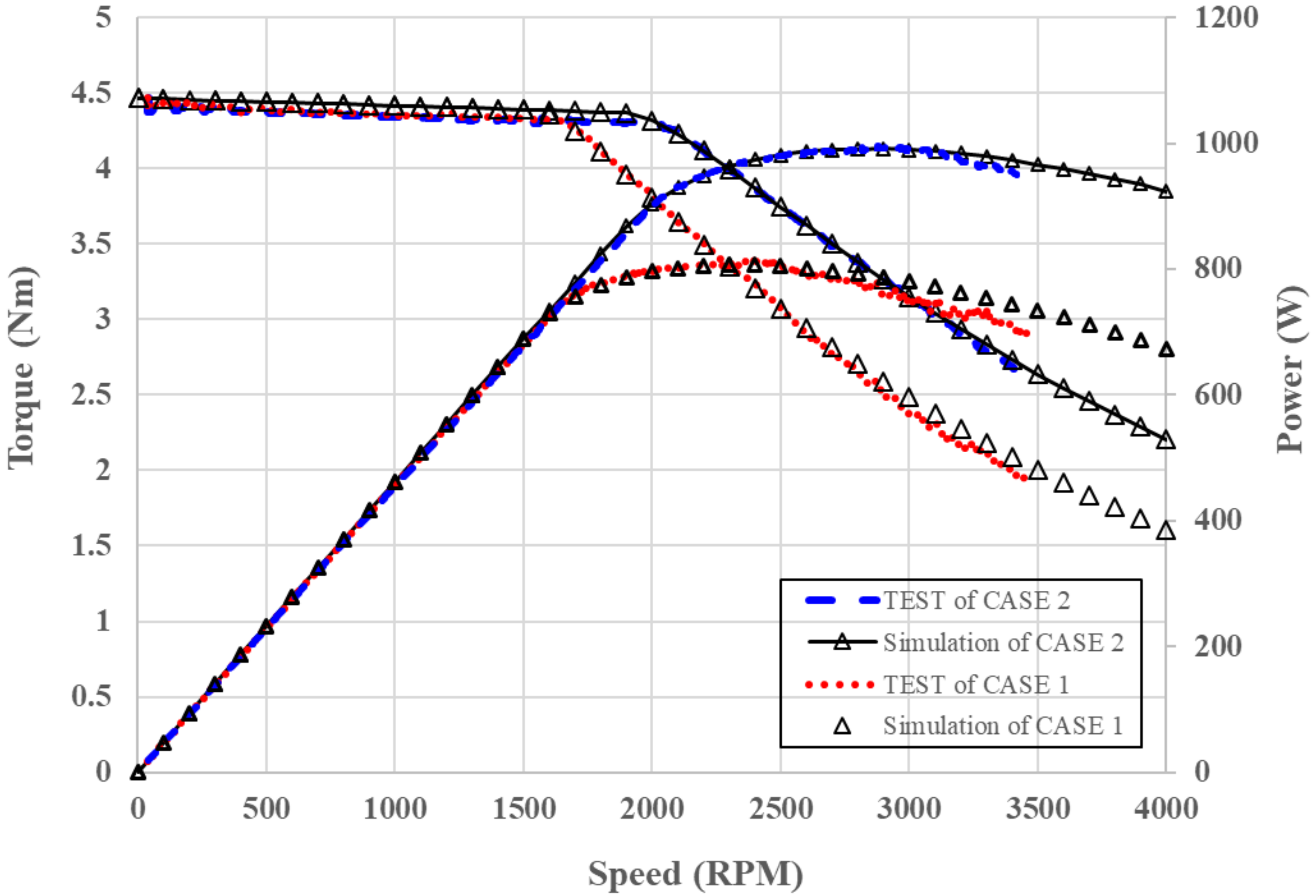
➢ **Motor Sample Test**




| TEST | CASE 1 | CASE 2 |
|---|---|---|
| The line to line peak voltage | 10.5 V | 12.5 V |
| **The line to line peak current** | 120 A | |

# Verification

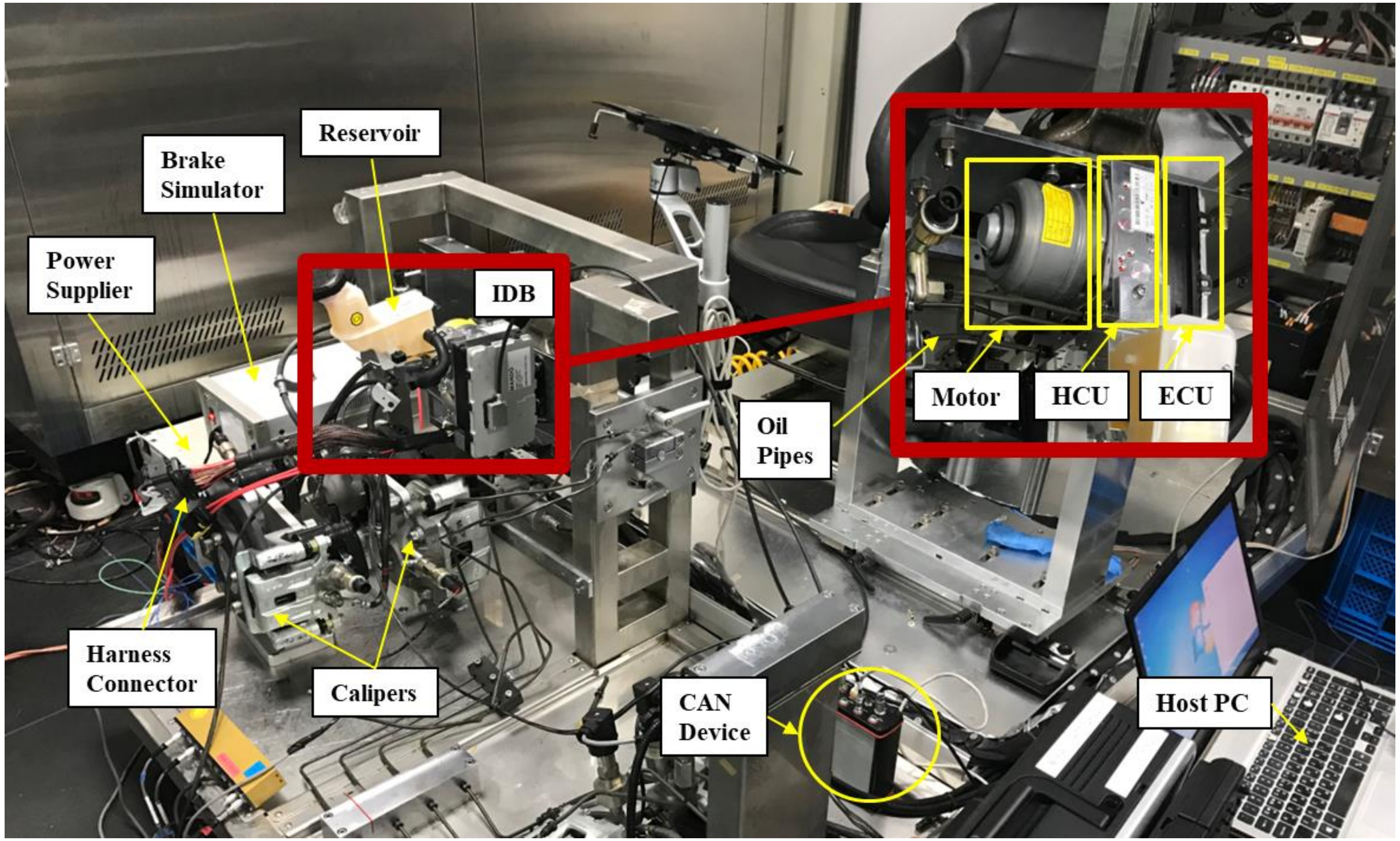
## ➢ Motor Sample Test Results(Torque, Power)




**Motor Model & Performance Verification**

# Verification

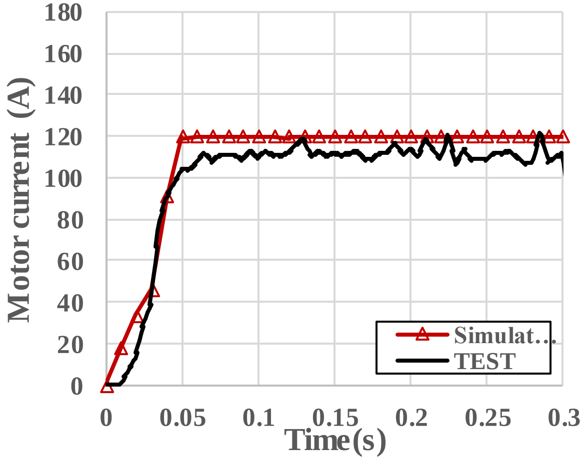
➢ **IDB2 System Performance Test (AEB)**



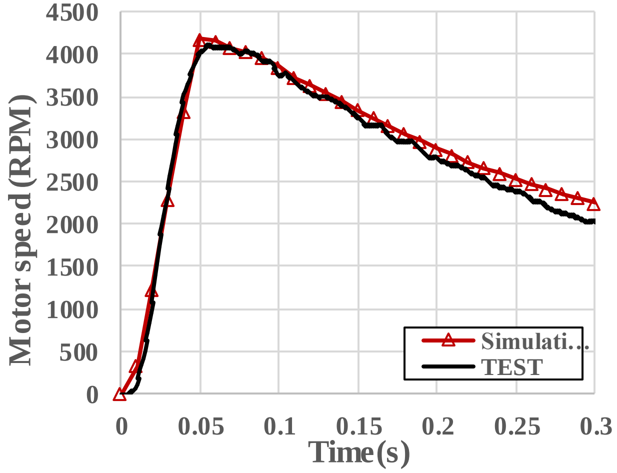
# Verification

## ➢ IDB2 System Performance Test Results (AEB)

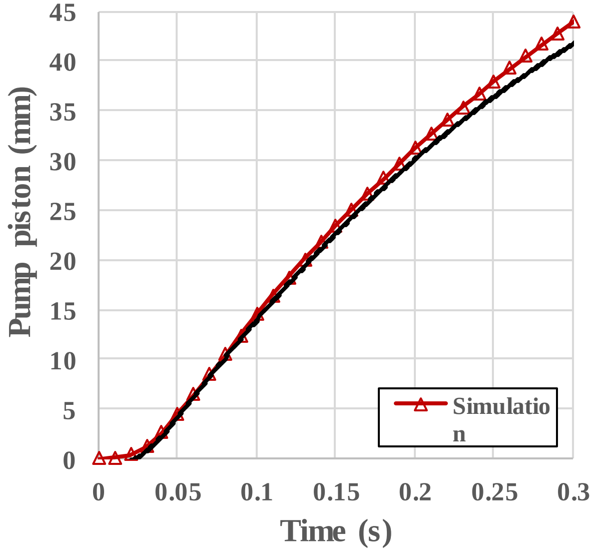
Current



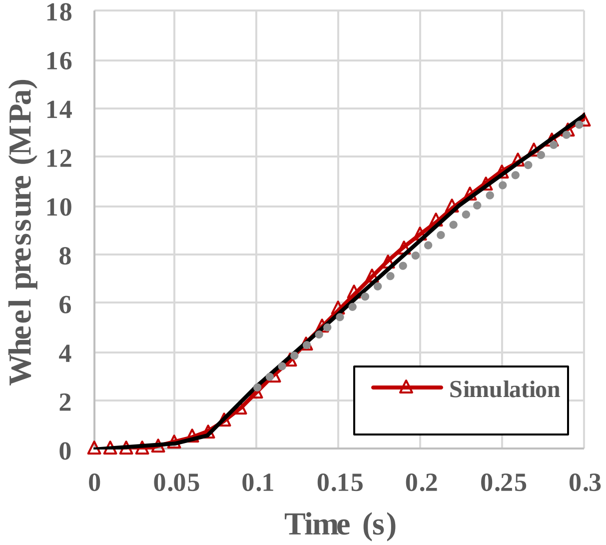

Speed




PiSTon



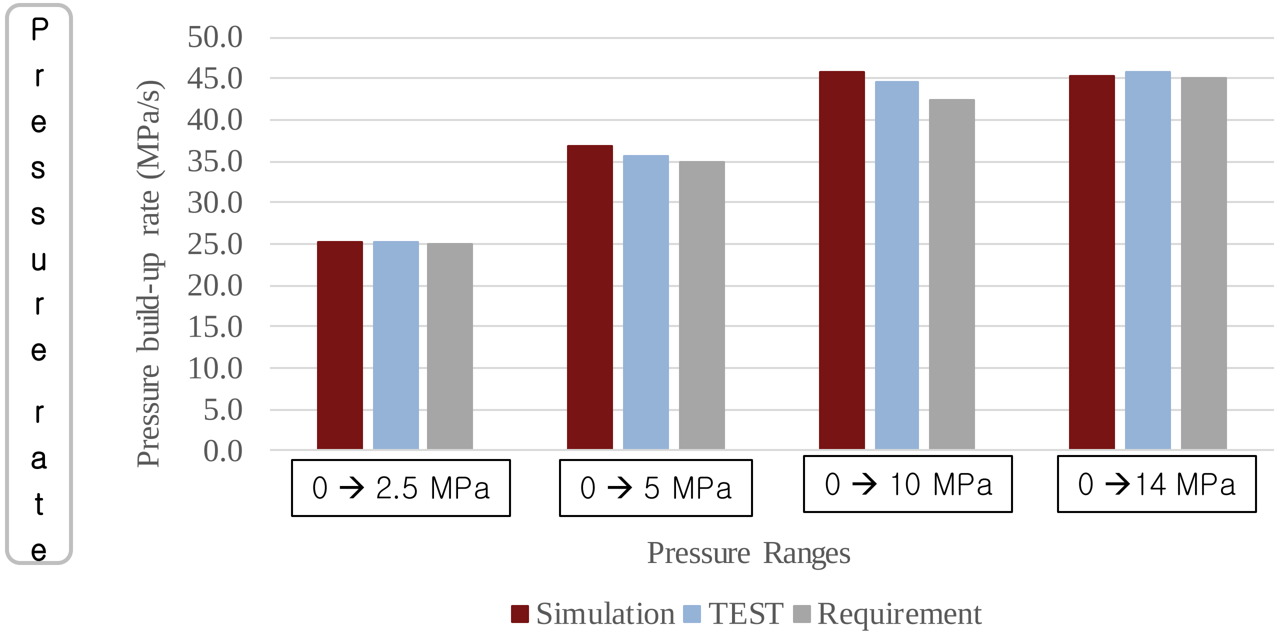

Pressure




**System model & Performance Verification**

# Verification

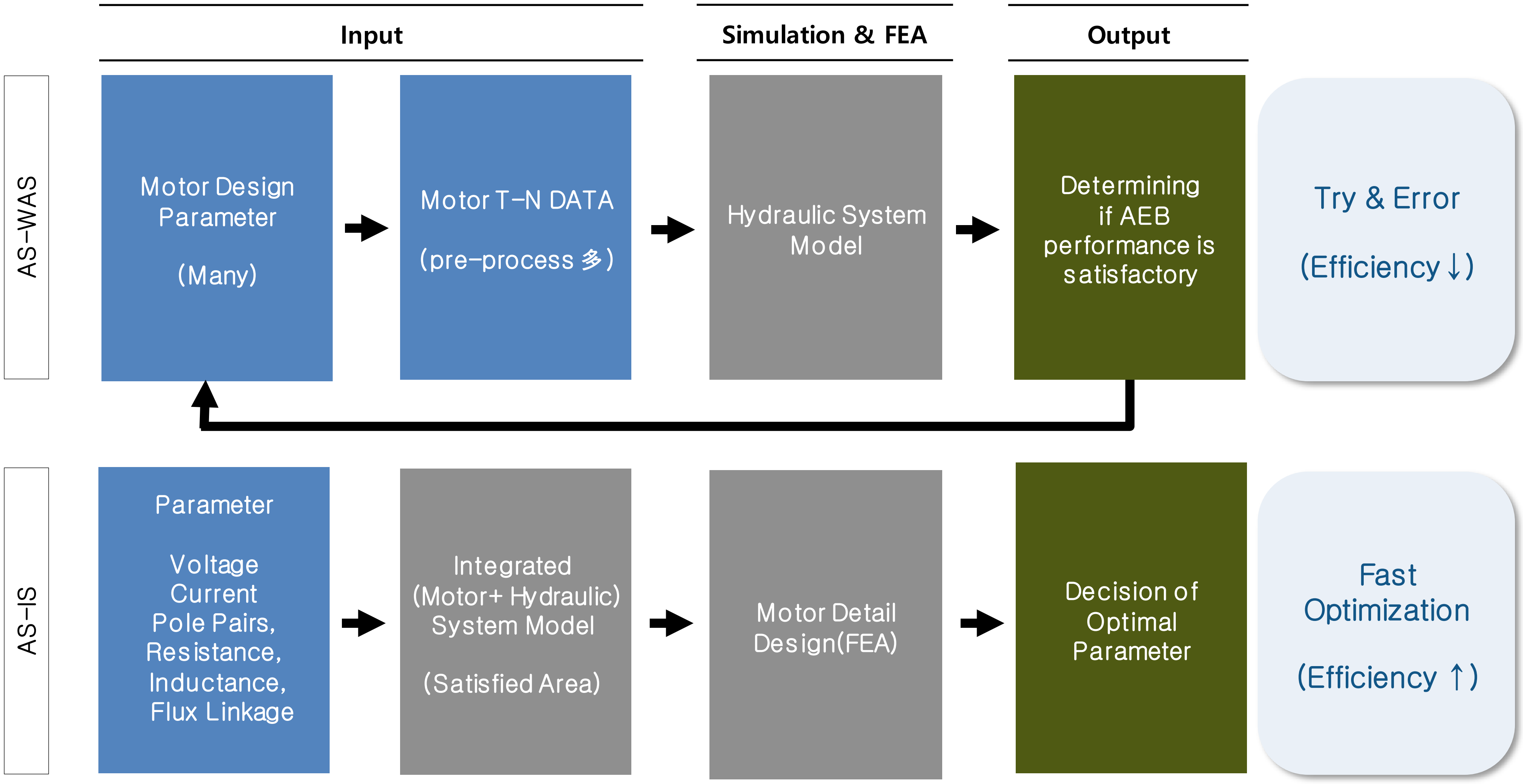
## ➢ IDB2 System Performance Test Results (Pressure build-up rate)




| Range | Requirement | Simulation | Test | Result |
|---|---|---|---|---|
| 0→2.5 MPa | ≥ 25 MPa/s | 25.3 MPa/s | 25.2 MPa/s | PASS |
| 0→5 MPa | ≥ 35 MPa/s | 36.8 MPa/s | 35.7 MPa/s | PASS |
| 0→10 MPa | ≥ 42.5 MPa/s | 45.9 MPa/s | 44.6 MPa/s | PASS |
| 0→14 MPa | ≥ 45 MPa/s | 45.4 MPa/s | 45.7 MPa/s | PASS |

Test–Simulation More than 95% Correlation

# AS-WAS vs. AS-IS



# Contents

# Summary

## 1. Motor Parametric Design Results

1) Motor + hydraulic integrated system model

2) 1D system simulation + FEA → optimal motor design

3) Test-simulation correlation

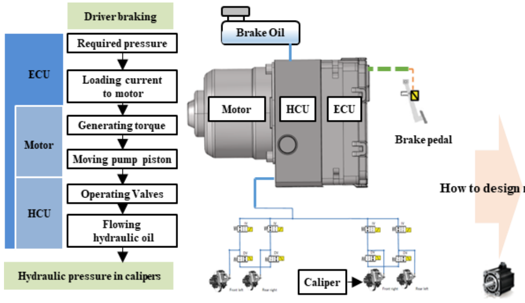
→ Motor & system performance verification

## 2. Advantage/Expansion

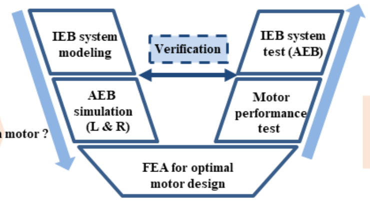
1) Maximize efficiency in selecting optimal motor design parameters

2) The more different vehicles and the more complex the system, the more efficient it is.

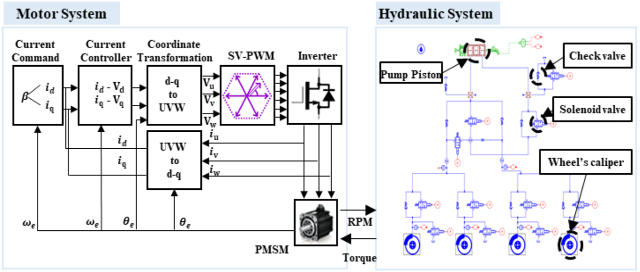
3) Applied outside the brake product line



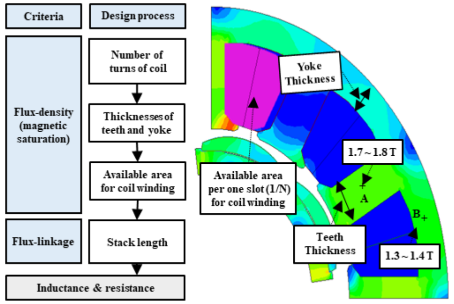

AEB requirement of IEB



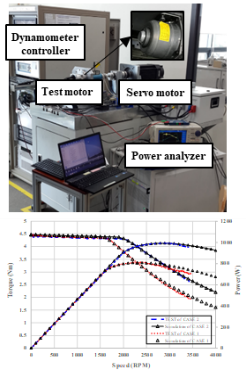

Motor design strategy of IEB



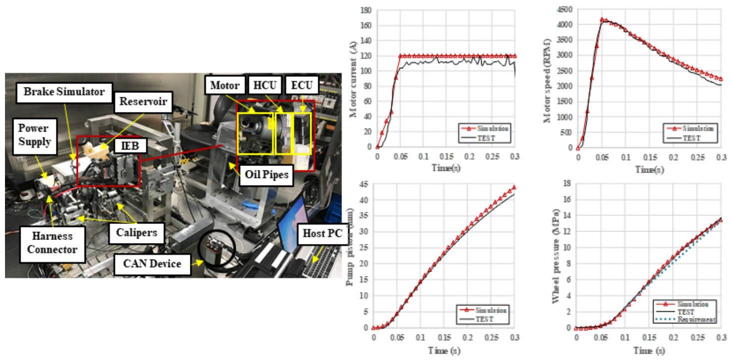

Find target motor parameters via Electro-Hydraulic Model




Motor design satisfies target parameters




Motor unit validation




AEB performance validation

MATLAB EXPO

# Thank you

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