A Numerical and Experimental Study on Dynamic Operation of a Synchronous Rotating Machine with NI HTS Field Windings

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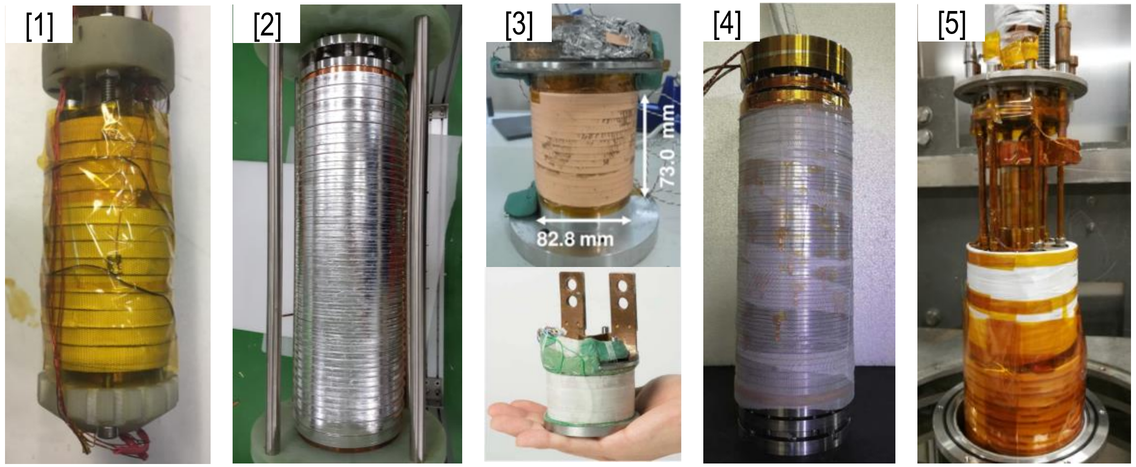
Contents

Considerations on No-Insulation Technique for HTS Rotating Machine

- No-Insulation and Metal-Insulation Technique
  - Successfully applied to high-field **“Stationary” “DC”** magnets
  - Pros: Better thermal protection of HTS coil
  - Cons: Turn-to-turn leak current

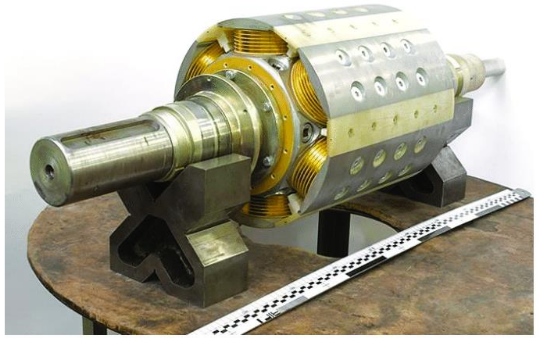


[1] 45.5 T High-field magnet by NHMFL-SNU
[2] 18 T Axion detector by IBS-SuNAM
[3] 31.4 T magnet by RIKEN
[4] 32.35 T High-field magnet by CAS
[5] 32.5 T High-field magnet by CEA&LNCMI-CNRS

- HTS Rotating Machine Application
  - HTS coils would be used as **“Rotary”** or **“AC”** magnets
  - Necessary to review whether NI works well in **“Rotary”** or ~~**“AC”** operation~~

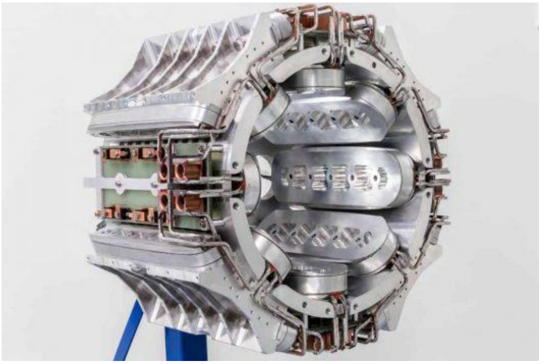
→ **in high frequency, leak current dominant**

Rotary DC field coil[6]



[6] HTS field coil for 200 kW motor by MAI

Stationary **AC** armature coil[7]



[7] Superconducting armature coil by MagniX

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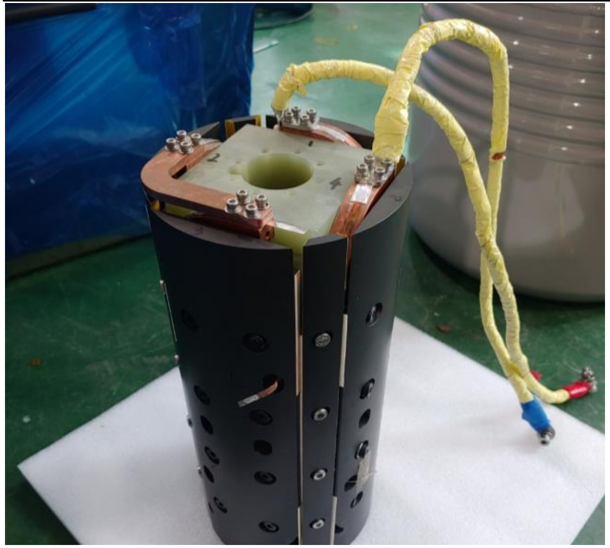
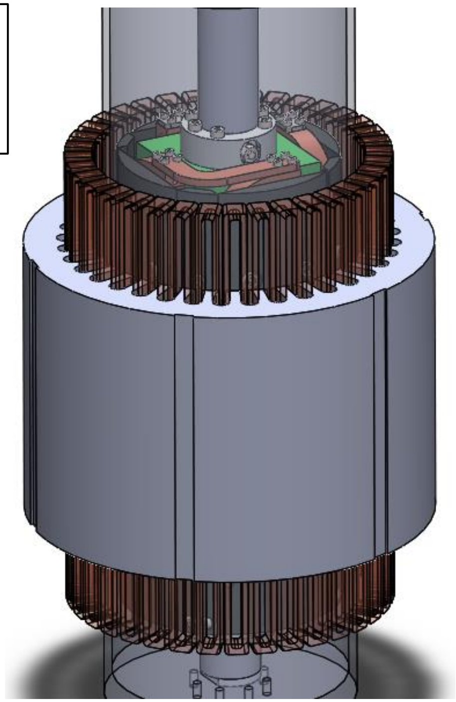
Overview on NI HTS Rotating Machine Project

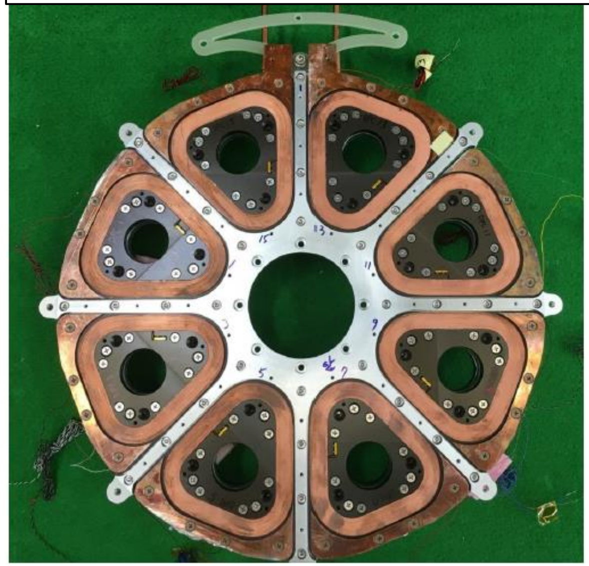
- Then, NI Coils for Field Coils?
  - "Rotary" + "**DC**" magnets → **<u>NI characteristic analysis</u>** by experiments & simulations

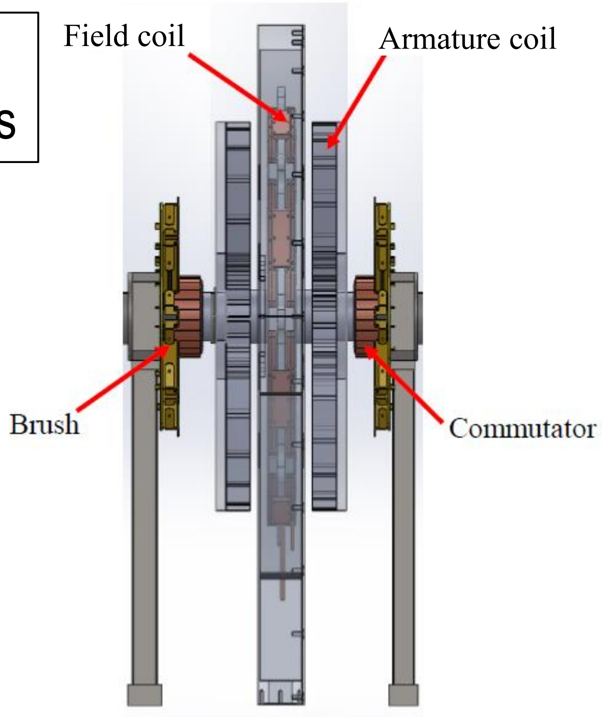
Team 1: Radial-flux type
Univ. research team & KERI





Team 2: Axial-flux type
Supergenics & Hyundai motors





- Next Step: Design of a Hundreds of kW Class HTS Motor with High Power Density
  - Collaboration project with Hyundai motors, Supergenics, Changwon National University

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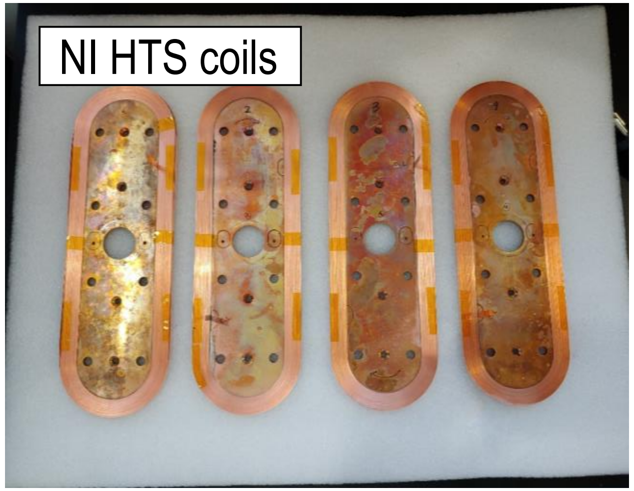
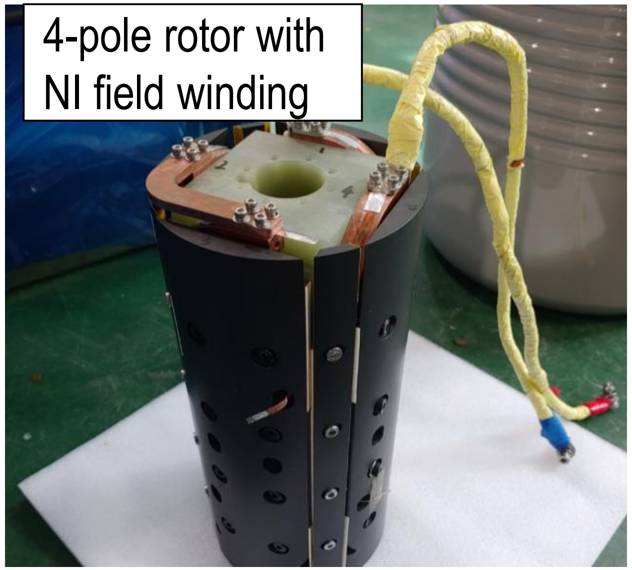
Contents

NI Field Windings and Experimental Setup

■ Key Parameters of Machine and NI Field Winding

Parameters	Unit	Values
Designed Machine Performance		
Output power	[W]	419
Coil phase current	[A_{rms}]	28.5
Coil phase voltage	[V_{rms}]	9.31
No-load voltage	[V_{rms}]	4.95
Rotating speed	[rpm]	300
Output torque	[Nm]	13.3
NI Racetrack Field Coils		
Effective length; inner radius; thickness	[mm]	180; 28; 4.1
Turns of racetrack coil	[-]	50
Operating temperature	[K]	77 (LN2)
Rated operating current @ 77K	[A]	67
Coil Inductance	[mH]	1.19
Characteristic resistance	[$\mu\Omega$]	142; 229; 197; 262
Charging time constant	[s]	8.45; 5.14; 6.10; 4.58





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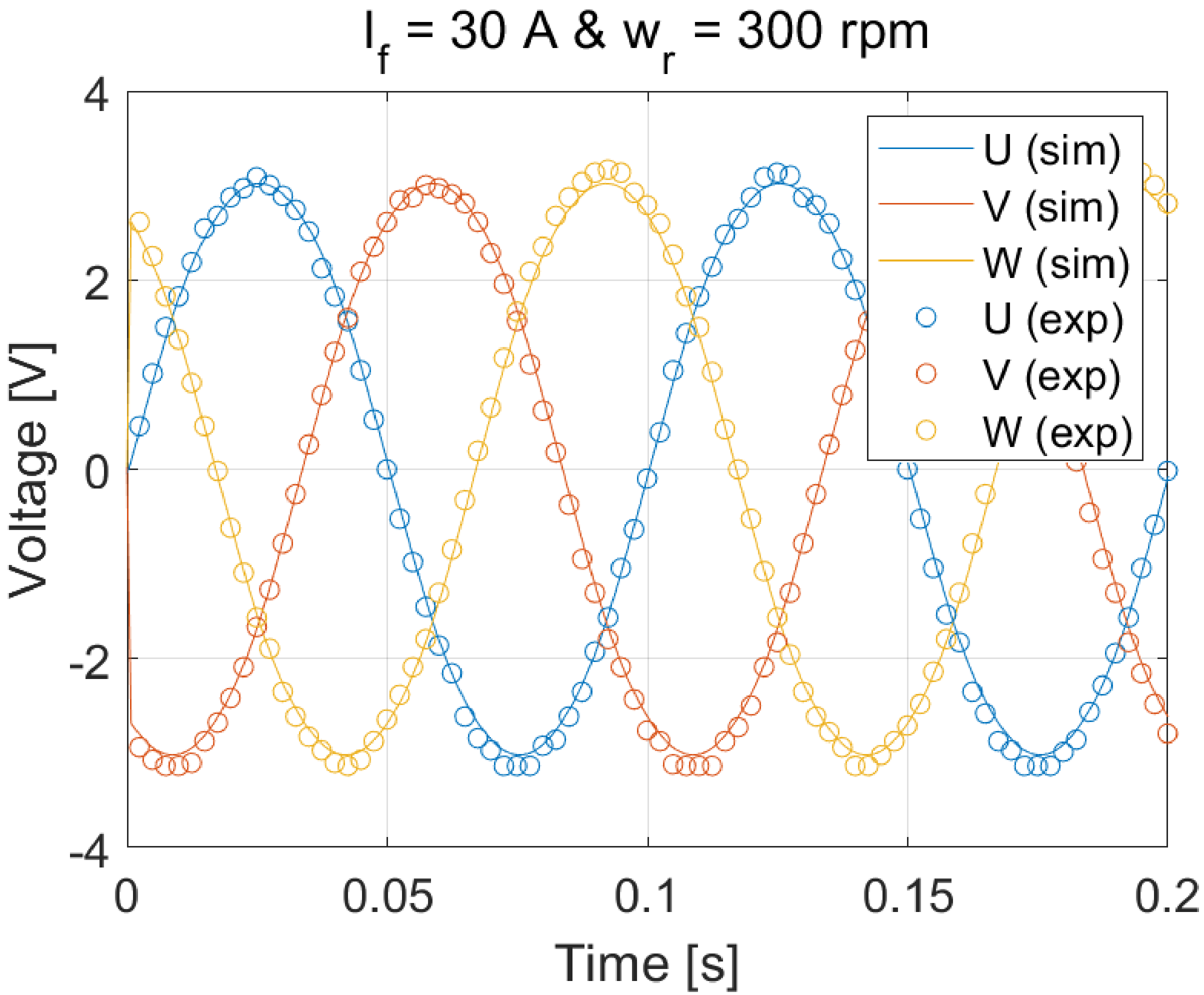
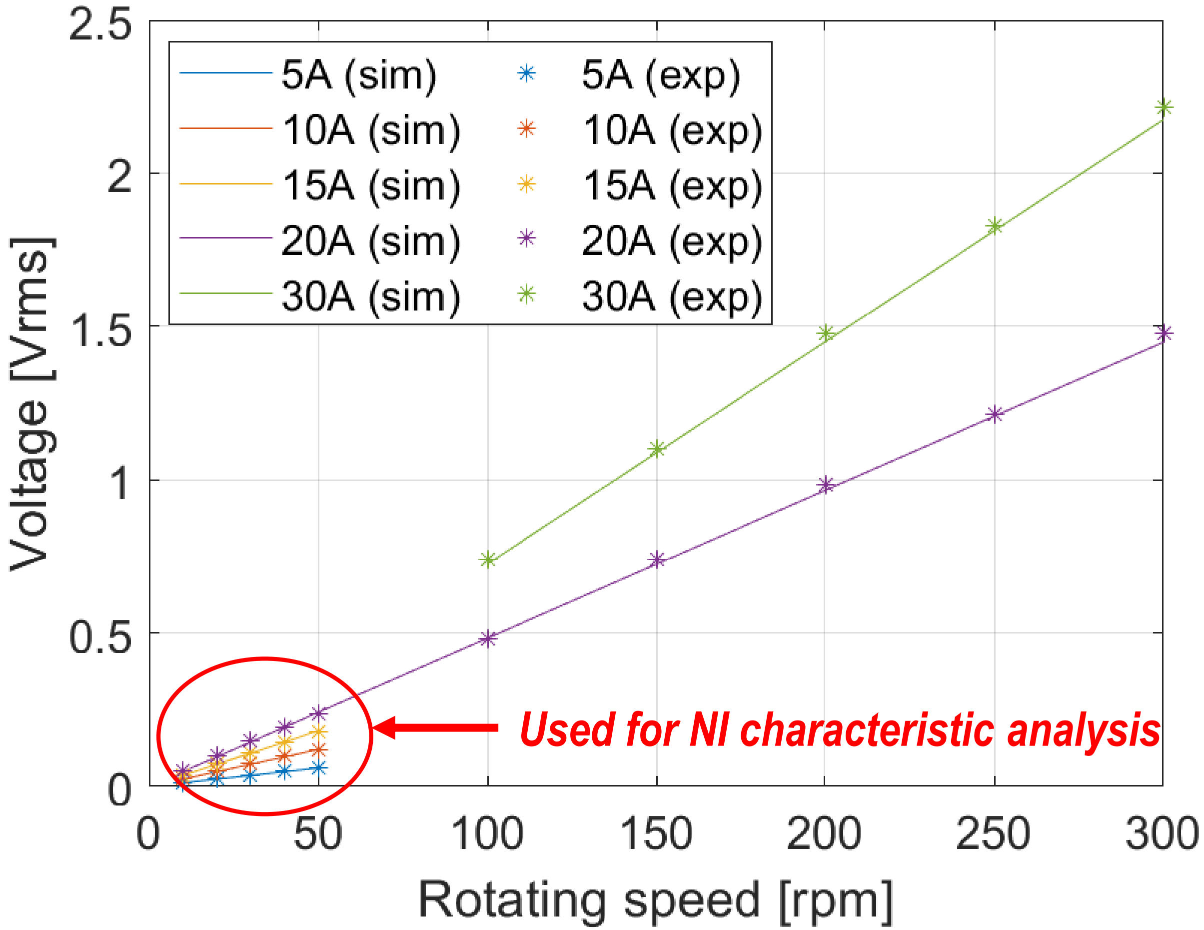
Operation Results in Generator Mode: 3-phase Voltage

- Comparison between Experiment and Simulation on Back EMF Tests
  - Simulation assumed **"<u>insulated</u>"** field coil → **no degradation due to NI in generator mode**





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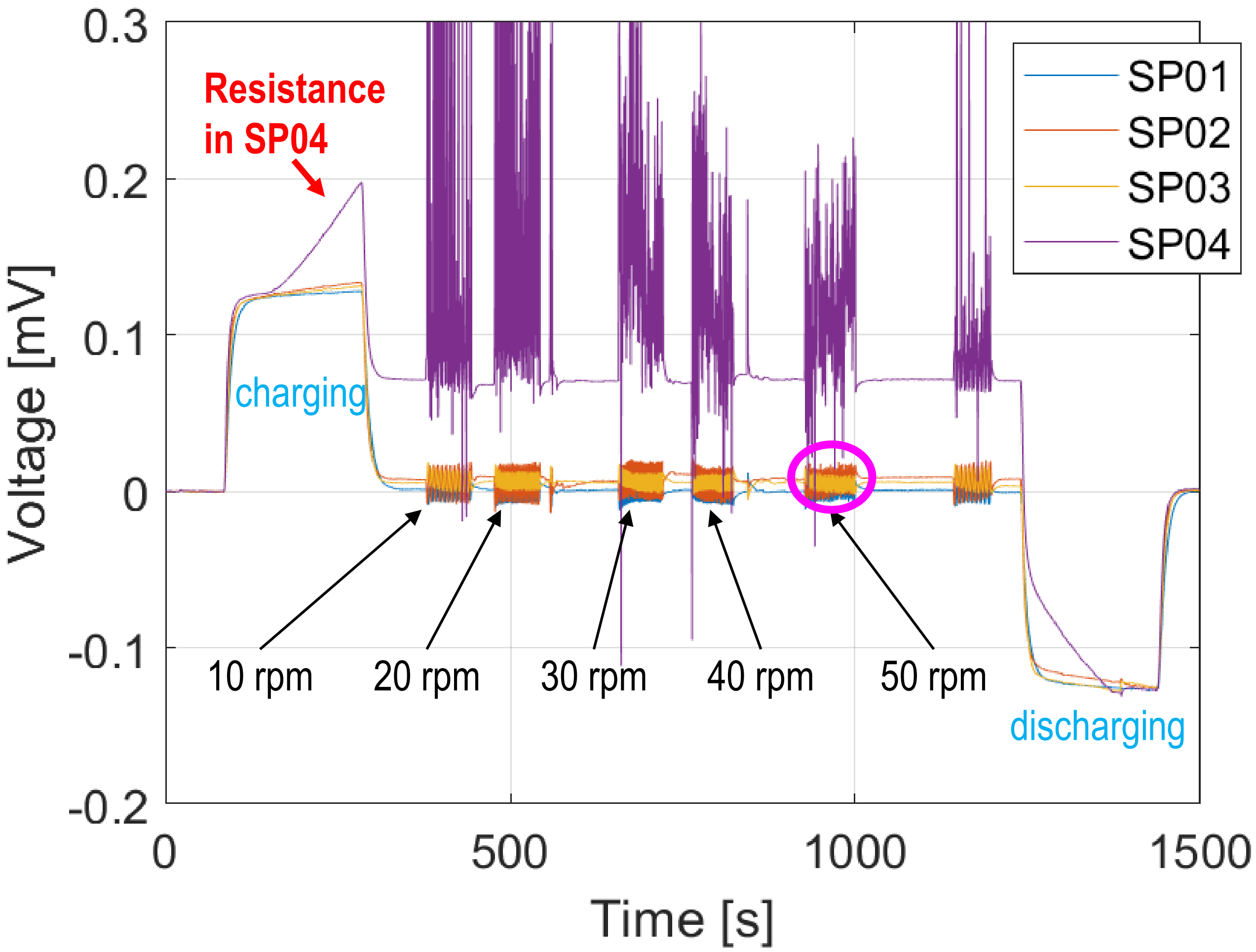
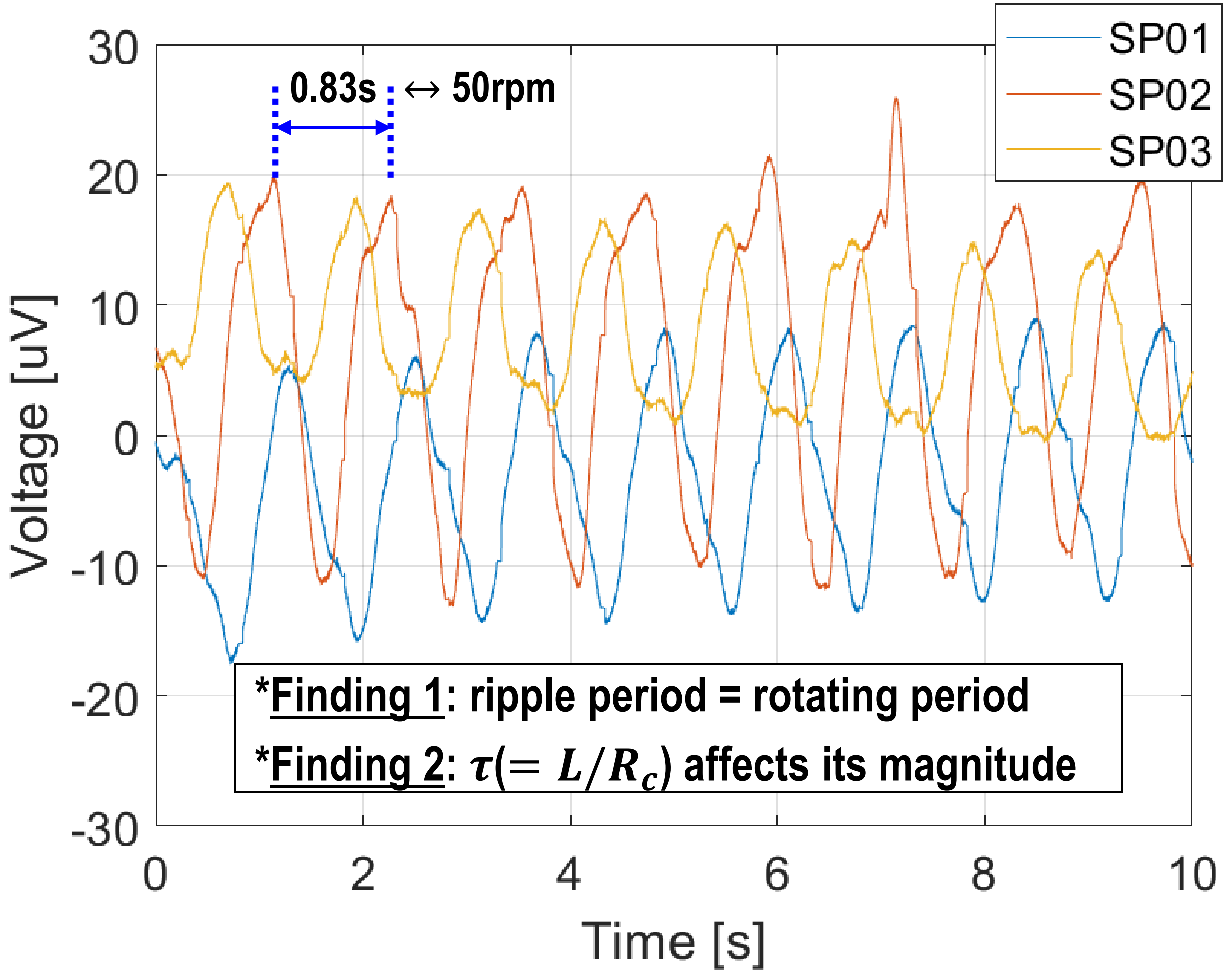
Operation Results in Generator Mode: NI Field Coils' Voltage

- Overall Voltage Profiles of NI Coils during Generator Mode Test
  - Some **periodic voltage ripples** identified in tests; not identified in ideal simulation





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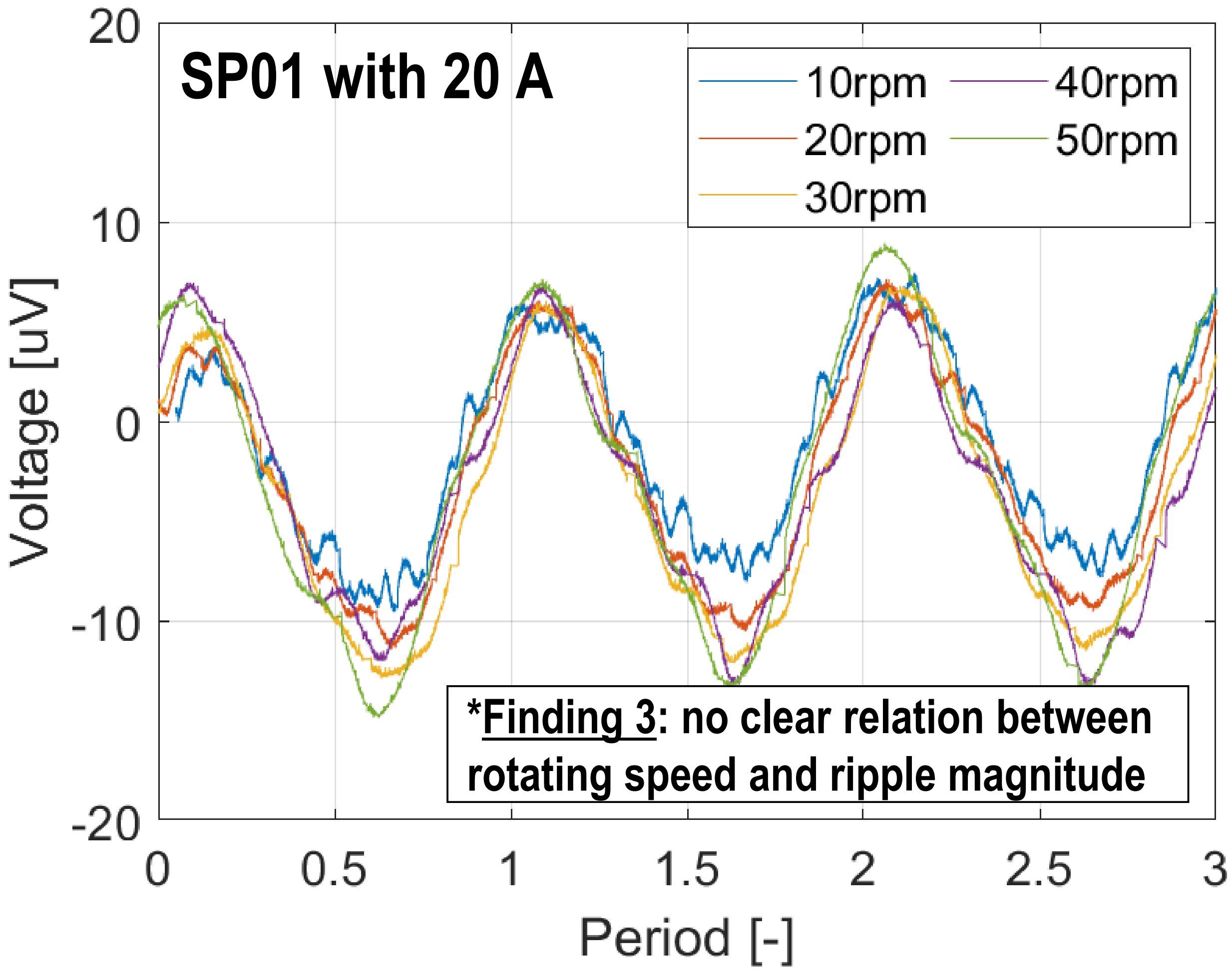
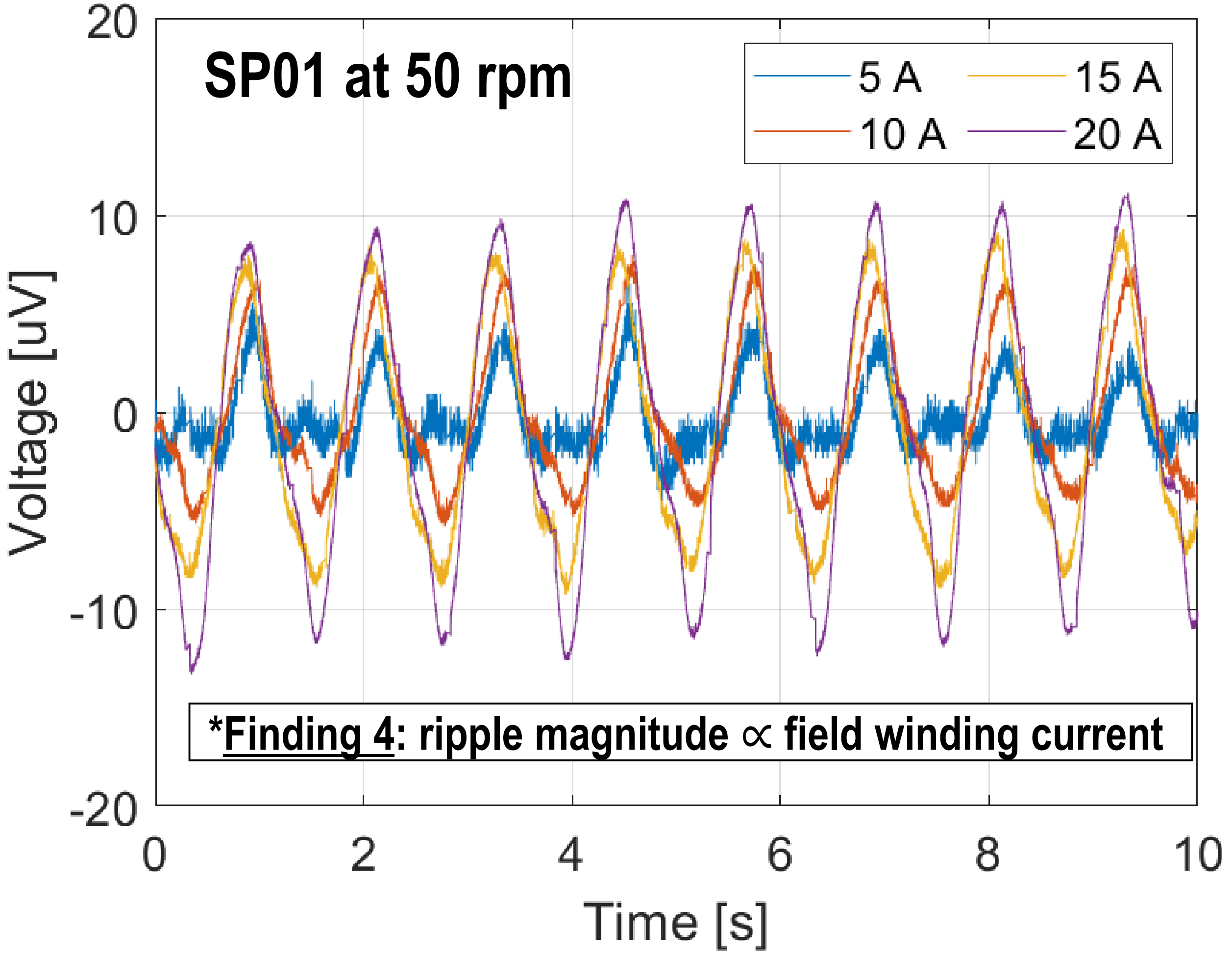
Operation Results in Generator Mode: NI Field Coils' Voltage

- Voltage Profiles of SP01 in Different Operating Conditions





- *These are **minor signals** (<sub-mV) in system view, but can we explain these ripples with our model?*

Contents

Explanation on NI's Electromagnetic Behavior in Generator Mode

■ Simplified Circuit Model of NI Coil in Generator Mode

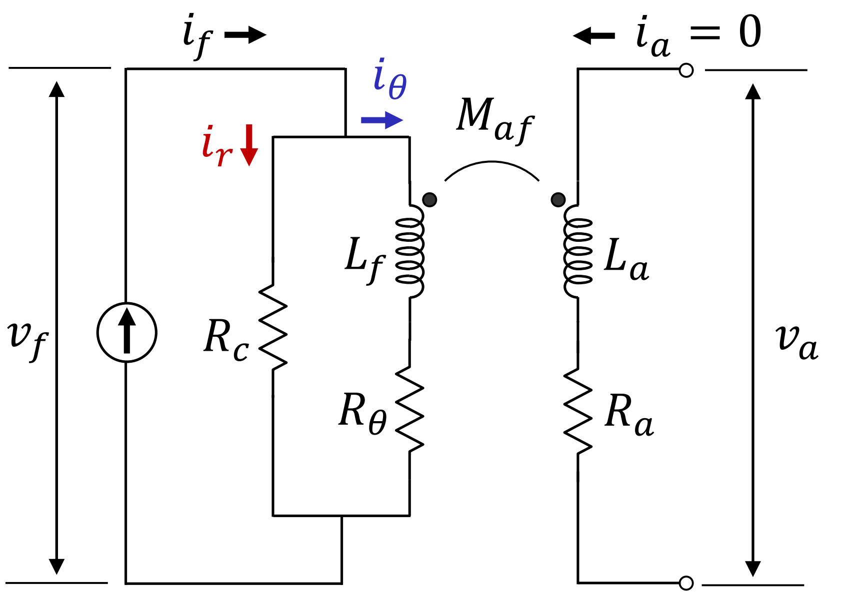
1 $v_f = \dfrac{d\lambda_f}{dt} + R_\theta i_\theta \qquad (\lambda_f = L_f i_\theta + M_{af} i_a)$

$= L_f \dfrac{di_\theta}{dt} + i_\theta \dfrac{dL_f}{dt} + M_{af} \dfrac{di_a}{dt} + i_a \dfrac{dM_{af}}{dt} + R_\theta i_\theta$

$= L_f \dfrac{di_\theta}{dt} + i_\theta \dfrac{dL_f}{dt} + R_\theta i_\theta$

2 $v_f = R_c i_r$

3 $i_f = i_\theta + i_r$

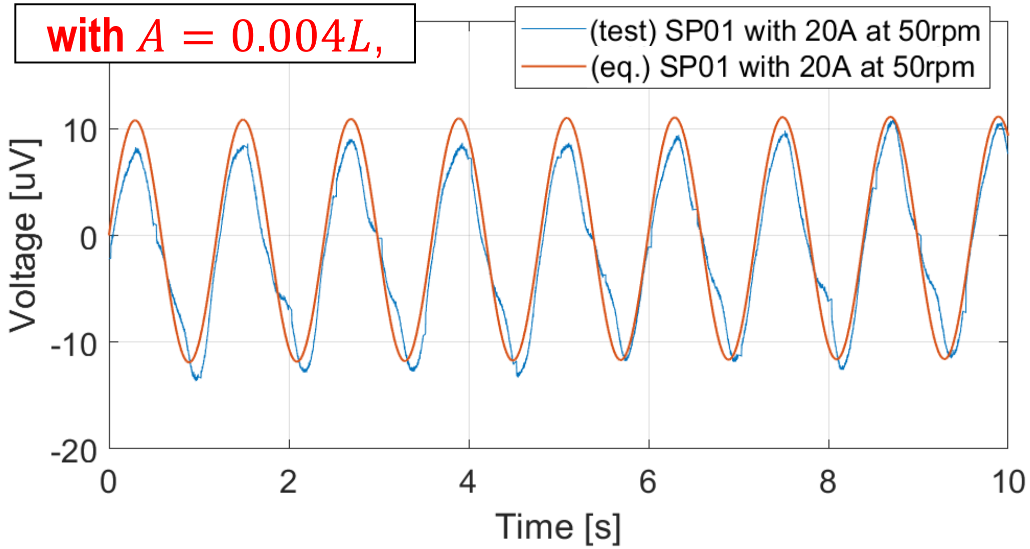


$$\boldsymbol{L_f \frac{di_\theta}{dt} + \left(\frac{dL_f}{dt} + R_c + R_\theta\right) i_\theta = R_c i_f}$$

Assume $\boldsymbol{L_f = L + A\sin\omega t,\ \dfrac{dL_f}{dt} = \omega A\cos\omega t}$,

$$(L + A\sin\omega t)\frac{di_\theta(t)}{dt} + (\omega A\cos\omega t + R_c + R_\theta)i_\theta(t) = R_c i_f$$

$i_\theta(0) = \dfrac{R_c}{R_c + R_\theta} i_f \qquad i_\theta(t) = ?$



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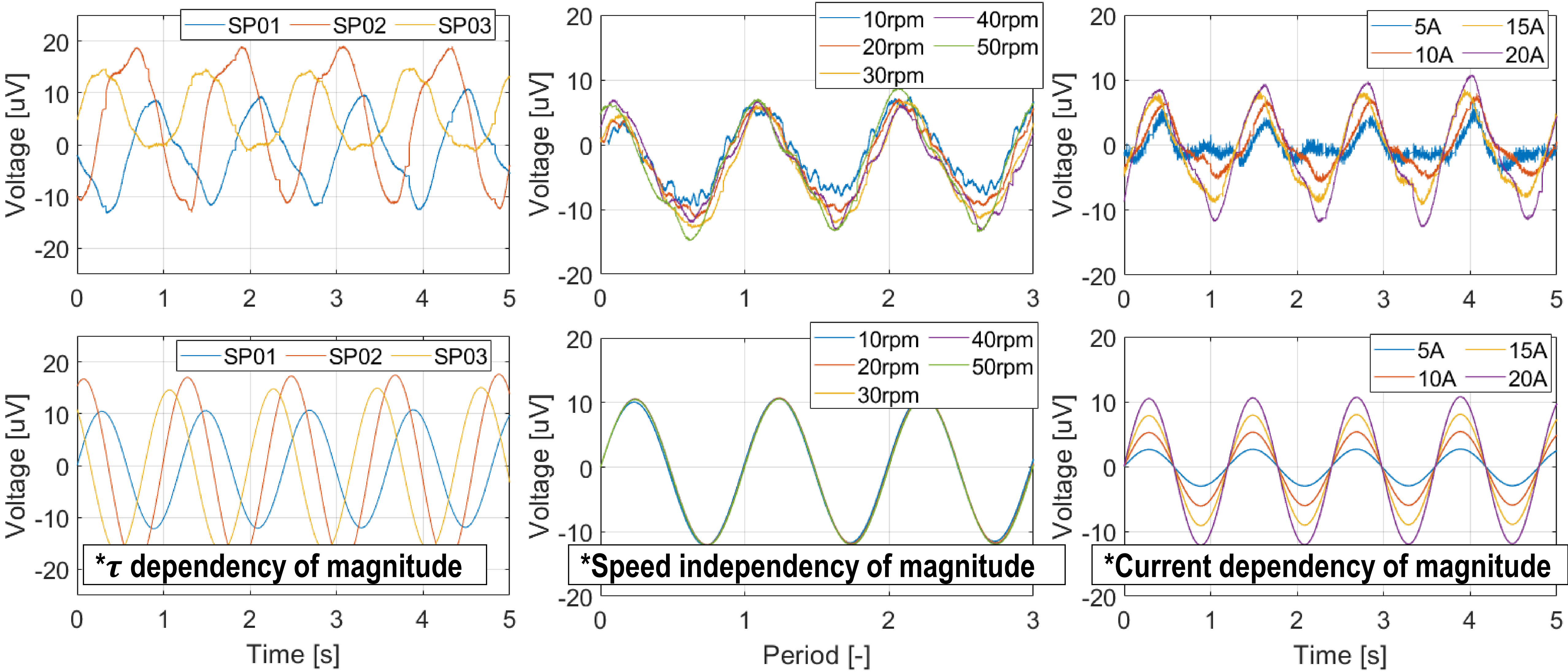
Explanation on NI's Electromagnetic Behavior in Generator Mode

- Duplication of Test Results with Assumption of $(L_f = L + 0.004L\sin\omega t)$



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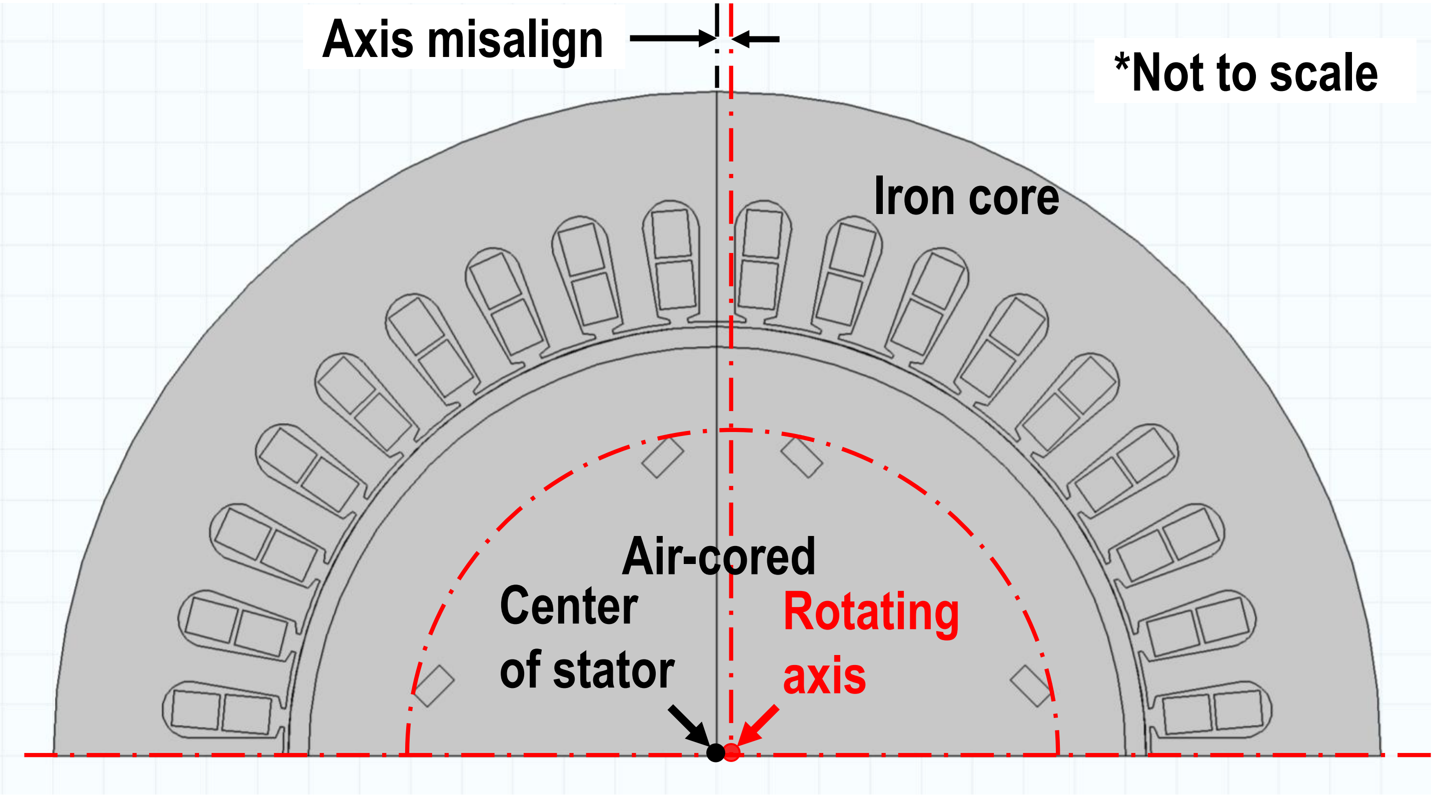
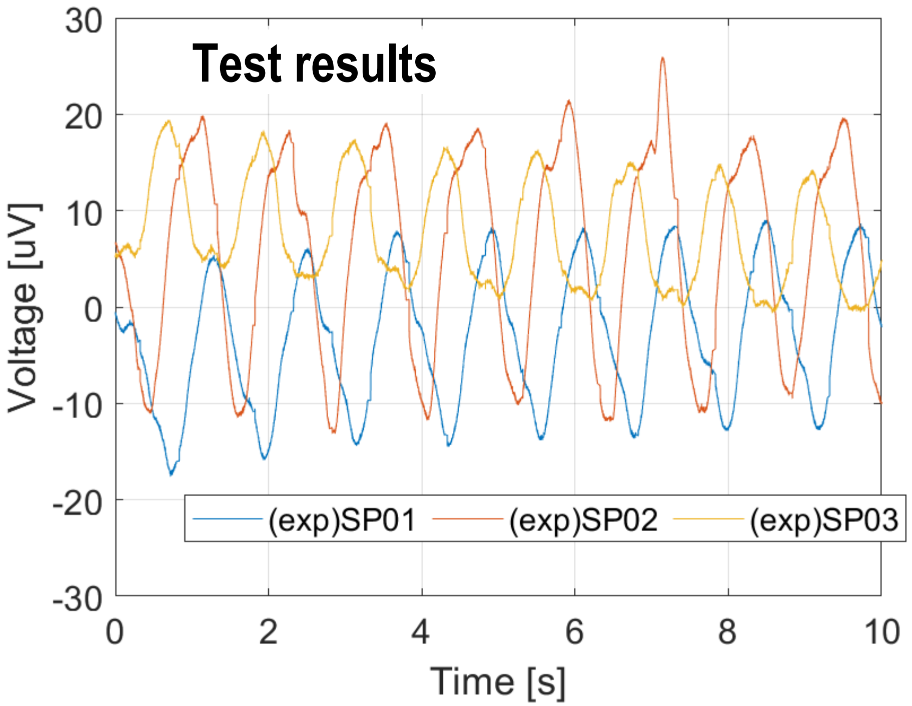
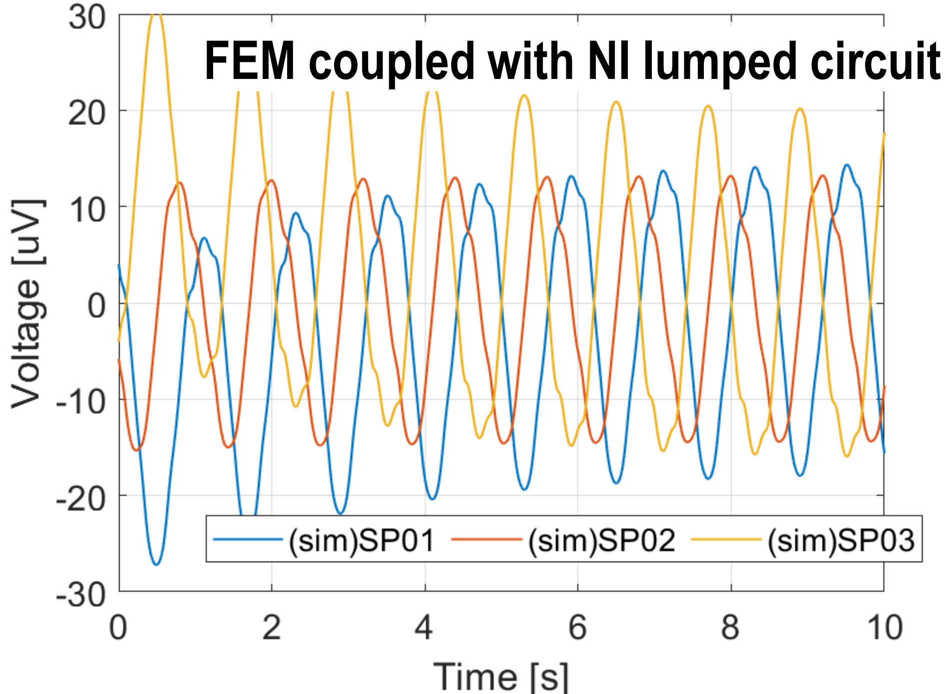
Explanation on NI's Electromagnetic Behavior

- Practical Reason for Inductance Variation in the Tests
  - □ One possible reason: **Eccentricity of axis**
  - □ → as coil become closer to iron, self-inductance ↑
  - □ → **<u>~0.15 mm of misalignment</u>** shows similar results

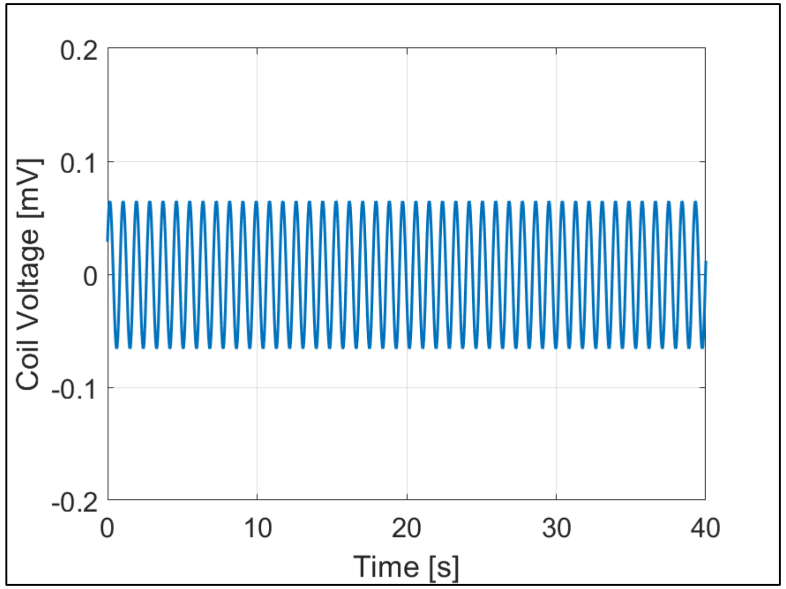


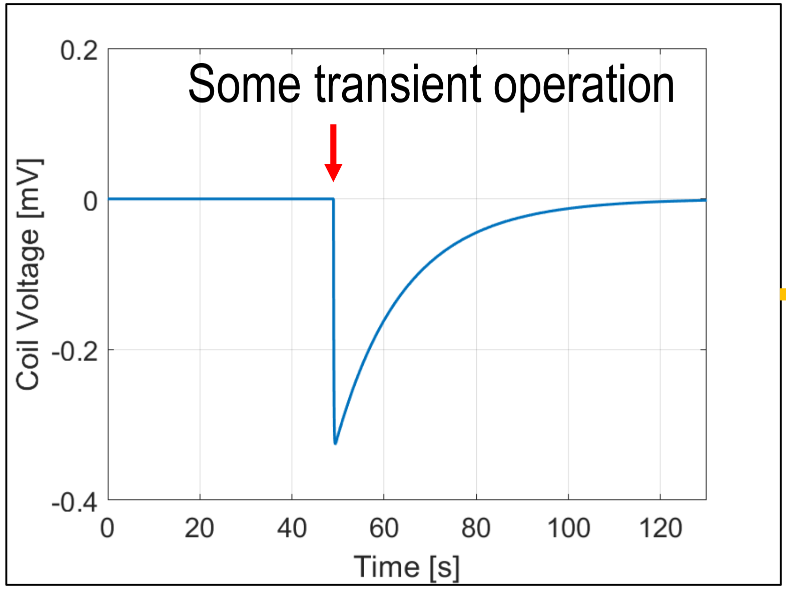


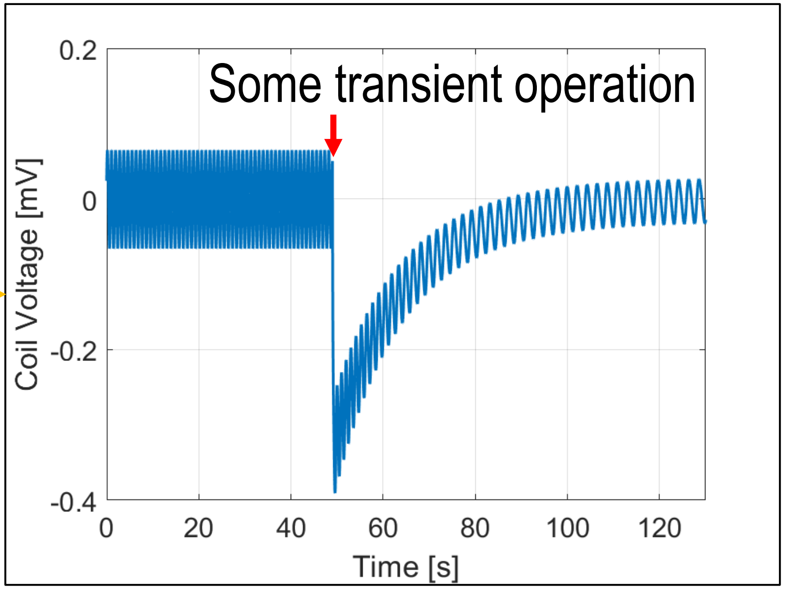


Expectation on NI Behavior of NI Synchronous Motor by Simulation

- Whole NI Behavior in Motor Operation Obtained by Equivalent Circuit Simulation[8]







- ☐ Periodical ripples
- ☐ In rotation,
  - Steady-state operation
  - Transient operation
- ☐ Due to non-ideal condition

- ☐ NI-magnet like leak current
- ☐ In transient operation,
  - Acceleration/deceleration
  - Load change
- ☐ Due to NI characteristics itself

- ☐ **Total NI coil signals in motor operation**

Experiment results of motor operation will be presented soon!

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Contents

Summary

- No-Insulation Technique to HTS Motor
  - Not suitable for AC armature coils in high frequency, due to leak current
  - Suitable for DC field coils, but **need to understand NI characteristics** in transient operation

- Experimental Studies on NI HTS Machine In Progress
  - Radial-flux type synchronous machine **with rotary NI field winding** constructed
  - **Periodical voltage ripples** identified their trends analyzed in generator mode

- Numerical Analysis on NI Behavior of Test Results In Progress
  - **NI behavior in generator mode explained** with the suggested model
  - Simulation module for motor operation constructed, and ready to analyze test result !

Thank you for your attention

Any Questions or Comments ?

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (no. 2018R1A2B3009249).

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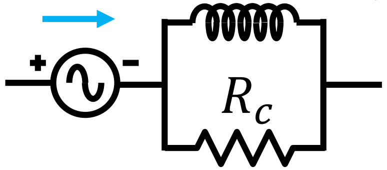
Appendix: Considerations on NI Technique for HTS Rotating Machine

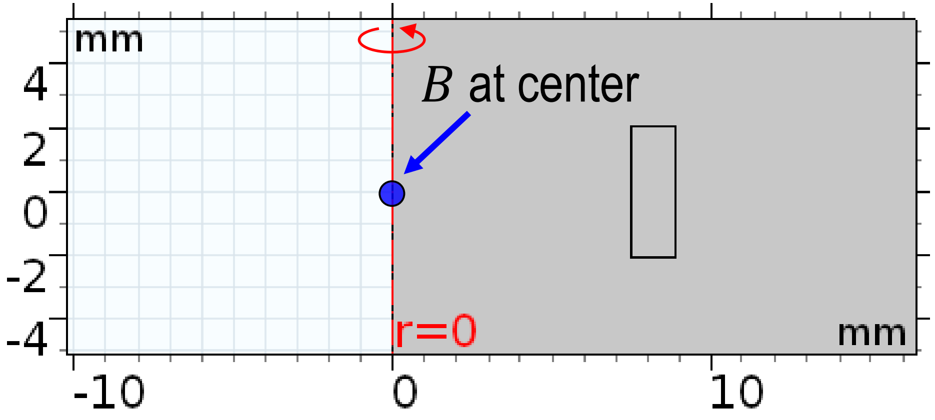
- Our Understanding on NI Coils with **"AC"** Current Operation So Far

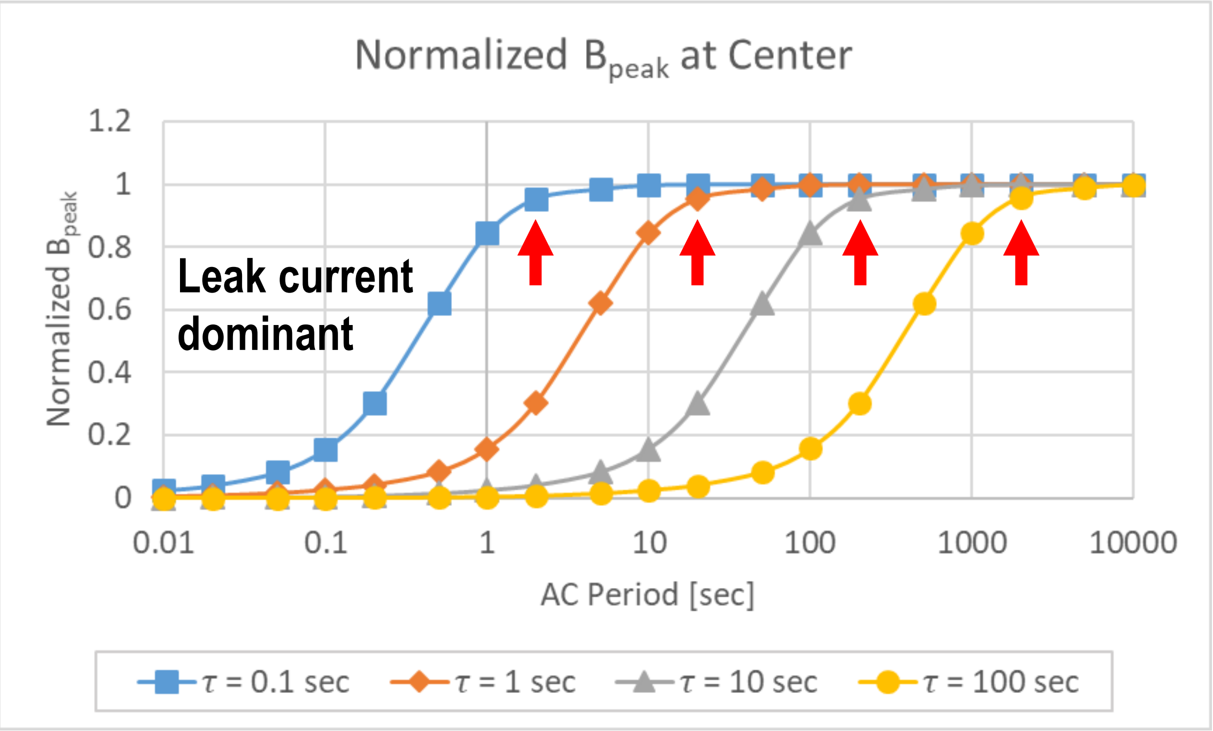
*Simple Case Study

$I = \sin(2\pi f t)$



$\tau = \frac{L}{R_c}$

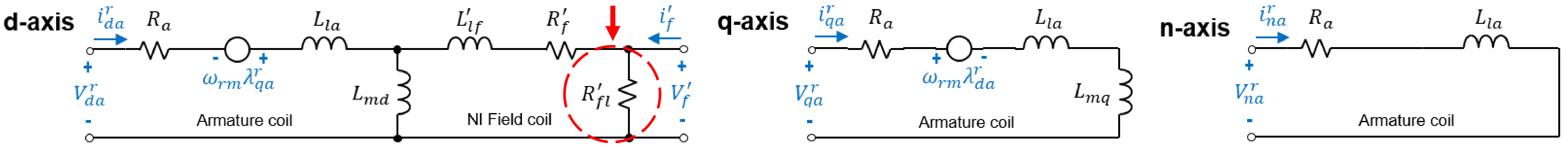




- ☐ At least NI coils' time constant should be 20 times smaller than operating AC period
  - When $\tau = 20/f$, 95 % of field generated as we intended (red arrow)
- ☐ **50 Hz Op. → Time constant < 1 ms**
- ☐ → *Further research to control time constant would be required for NI **AC** armature coils*

Appendix: Simulation Models for Synchronous Motor with NI Field Winding

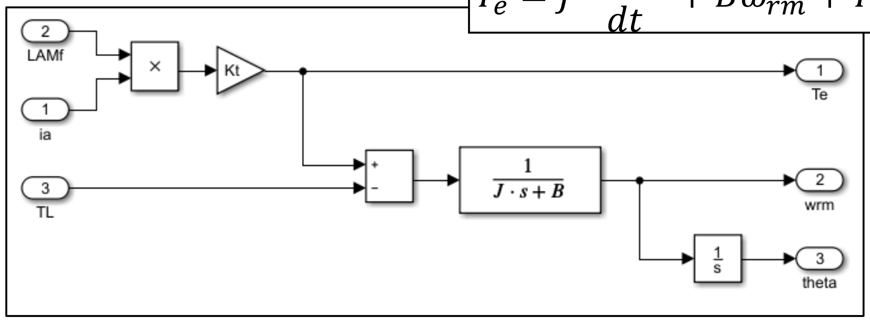
- Then, How Can We Expect NI Behavior in Motor Operation ?
  - Equivalent Circuit Modeling[8]: Rotor Reference dq-axis Circuit + **NI Lumped Circuit**

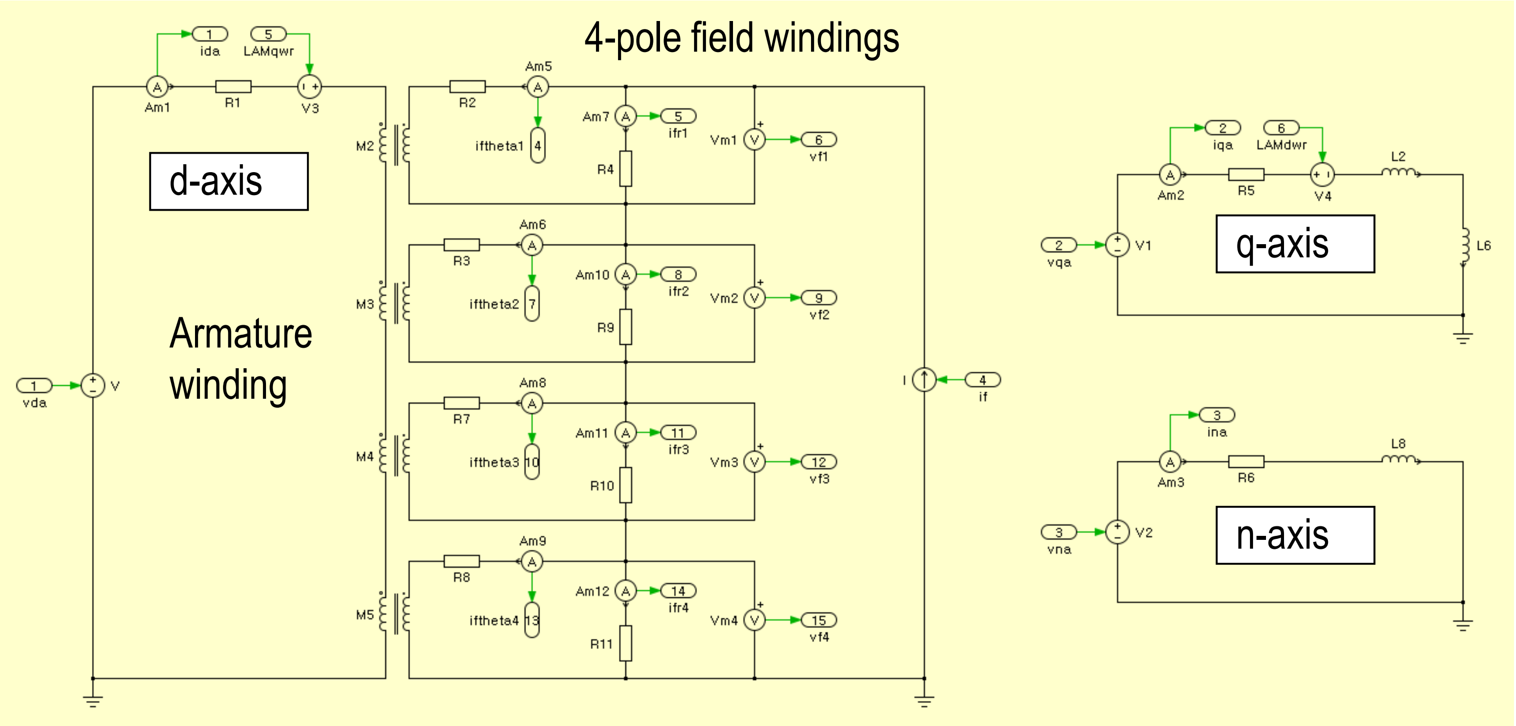


- Actual Implementation
  - (MATLAB Simulink + PLECS Circuit Simulator)

Mechanical model

$$T_e = J\frac{d\omega_{rm}}{dt} + B\omega_{rm} + T_L$$





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