

Electromagnetic Torque From Event Report Data – A Measure of Machine Performance

Derrick Haas and Dale Finney
Schweitzer Engineering Laboratories, Inc.

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Overview

- Electromagnetic torque calculation
- Modeling and validation
- Sources of error
- Real-world examples

Machine Equations

$$v_{qs} = R_s \cdot i_{qs} + \frac{\omega}{\omega_B} \cdot \Psi_{ds} + \frac{p}{\omega_B} \cdot \Psi_{qs}$$

$$v_{ds} = R_s \cdot i_{ds} - \frac{\omega}{\omega_B} \Psi_{qs} + \frac{p}{\omega_B} \Psi_{ds}$$

$$T_e = \Psi_{ds} \cdot i_{qs} - \Psi_{qs} \cdot i_{ds}$$

Integration to Calculate Flux

From machine equations, integrate voltages

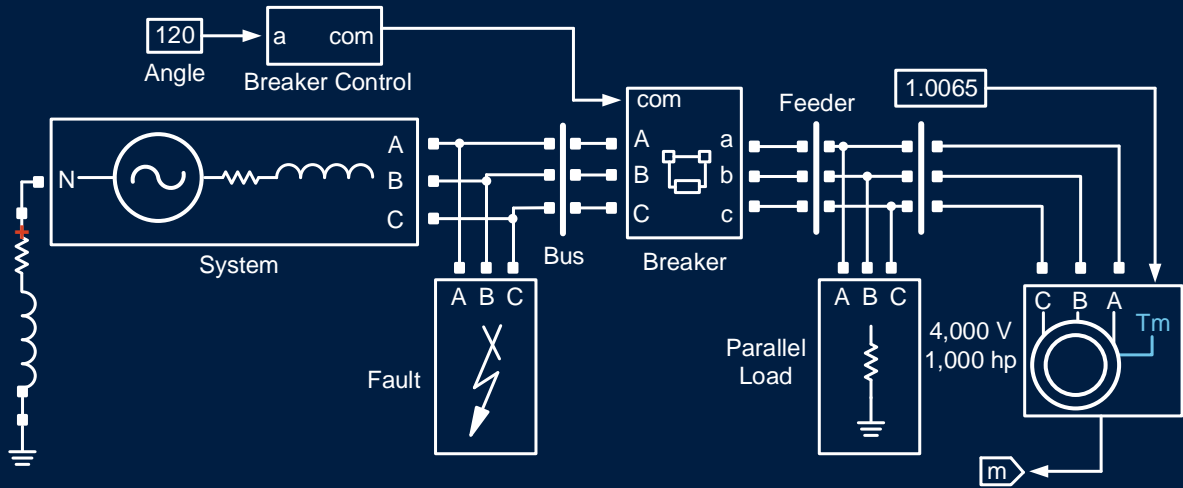
$$\Psi_{ds} = \omega_b \cdot \int (v_{ds} - R_s \cdot i_{ds})$$

$$\Psi_{qs} = \omega_b \cdot \int (v_{qs} - R_s \cdot i_{qs})$$

Numerical integration methods, such as trapezoidal rule, are required

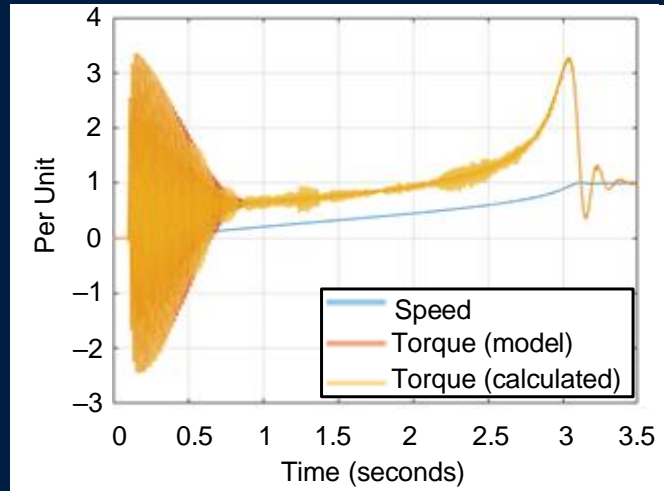
$$\int_i^{i+1} f(i) = \frac{h}{2} \cdot [f(i) + f(i+1)]$$

Dynamic Model

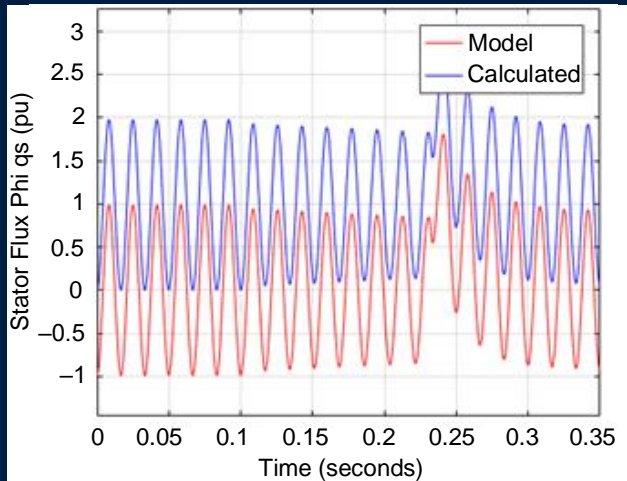


Validation

Comparison of Torque From Model and Calculation



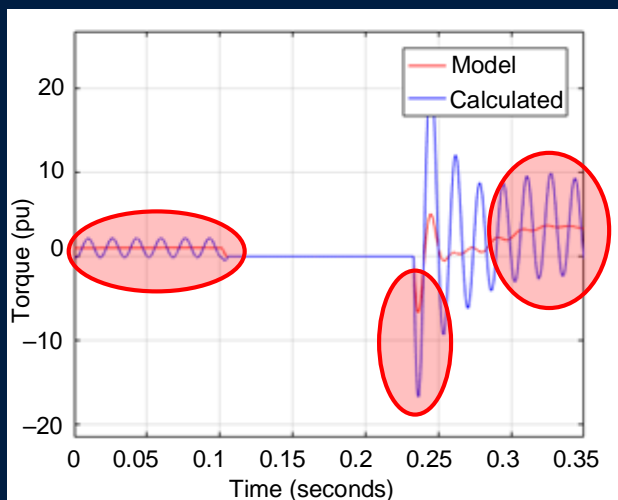
Error Sources Incorrect Initialization



- Expect no dc flux at steady state
- Begin integration whenever event report starts (arbitrary)
- Remove dc flux

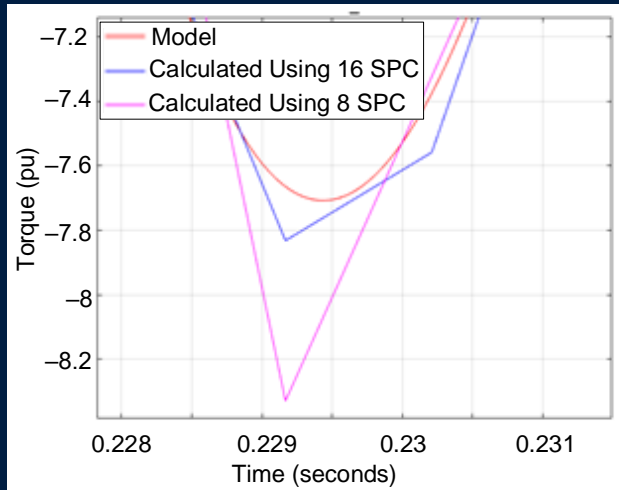
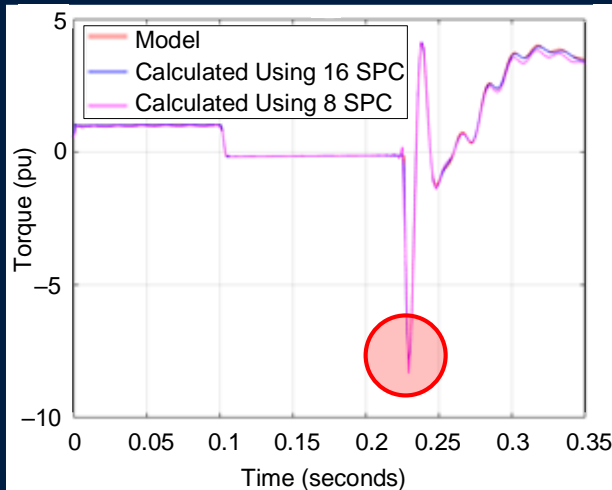
$$\Psi_{ds} = \omega_b \cdot \int (v_{ds} - R_s \cdot i_{qs}) - DC_d$$

Torque Error Incorrect Initialization



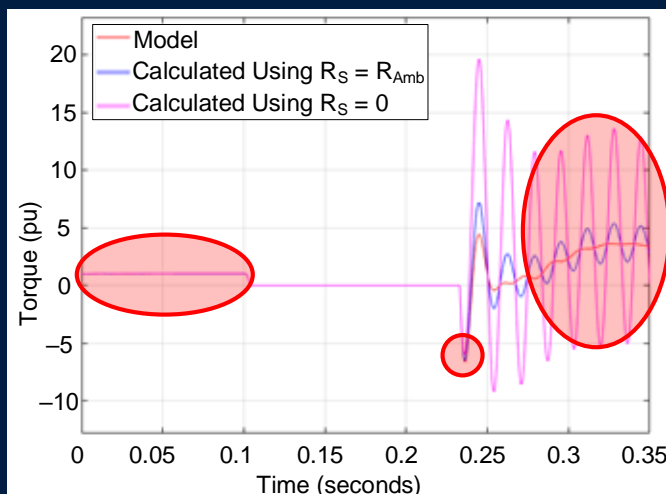
- Torque oscillations occur during prefault or preswitching
- Results in overestimate of peak torque
- High oscillations occur after fault or switching event

Error Source Sampling Rate



Error is 1.6% at 16 SPC and 8.1% at 8 SPC

Error Source Motor Stator Resistance

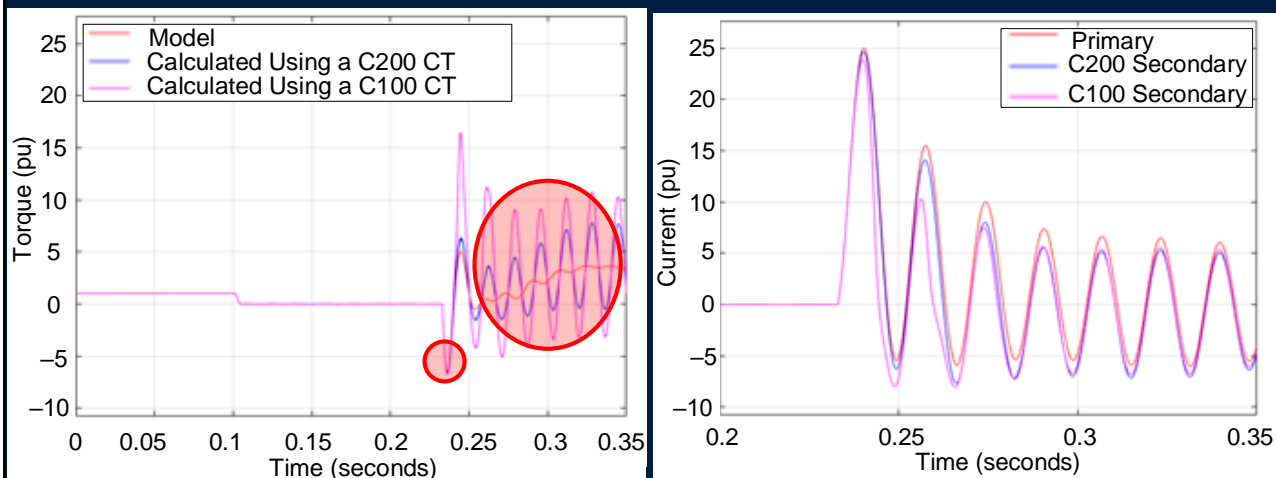


- R_S unknown or varied

$$\frac{\Delta R_S}{R_{Amb}} = \alpha \cdot \Delta T = 3.9 \cdot 10^{-3} \cdot 55 = 21.5\%$$

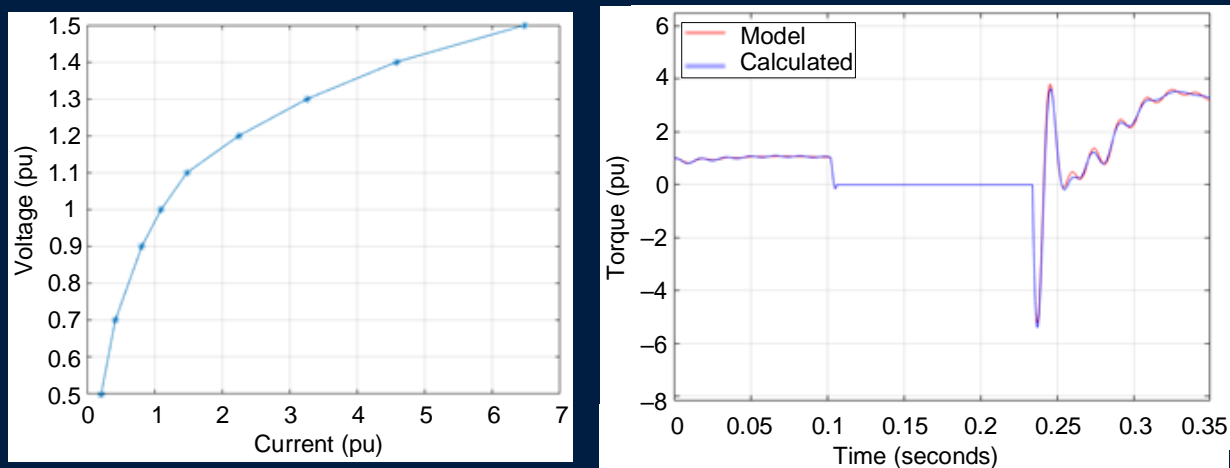
- No initial error
- First peak – 1.8% error
- Oscillations following switching event

Error Source CT Saturation



Error small for first peak, then increases as CT saturates

Error Source Core Saturation



Small impact – 3.6% error for peak torque

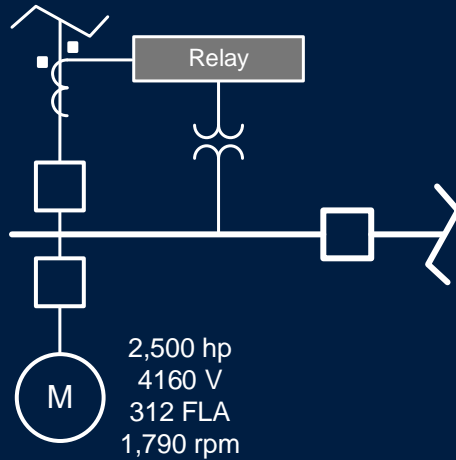
Simulations

- 308 test cases (128 terminal faults, 180 reclose events)
- Varied load, fault type, point-on-wave, and fault resistance for terminal faults
- Varied load and reclose angle for reclose events
- Largest error sources – stator resistance and CT saturation

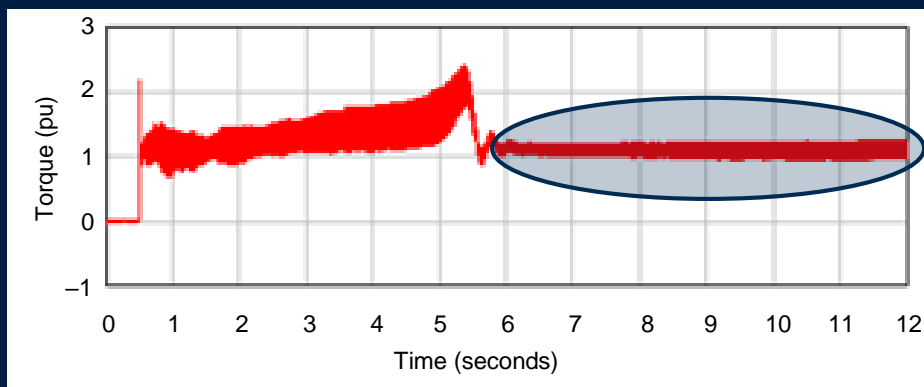
Summary of Errors

Stator Resistance Error (%)	First Peak Torque Error (%)			
	Terminal Faults		Out-of-Phase Reclosing	
	Avg	Max	Avg	Max
5	3.76	41.1	2.33	21.84
20	3.86	41.4	6.77	45.37

Example 1 – Start 2,500 hp Motor

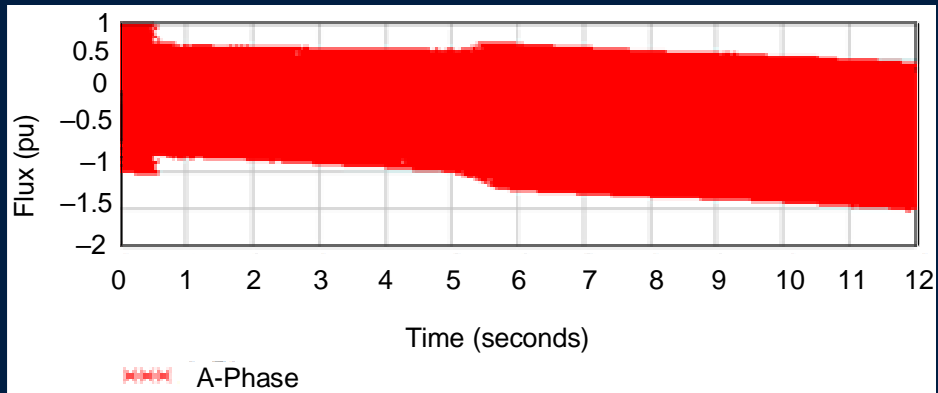


Torque With Errors



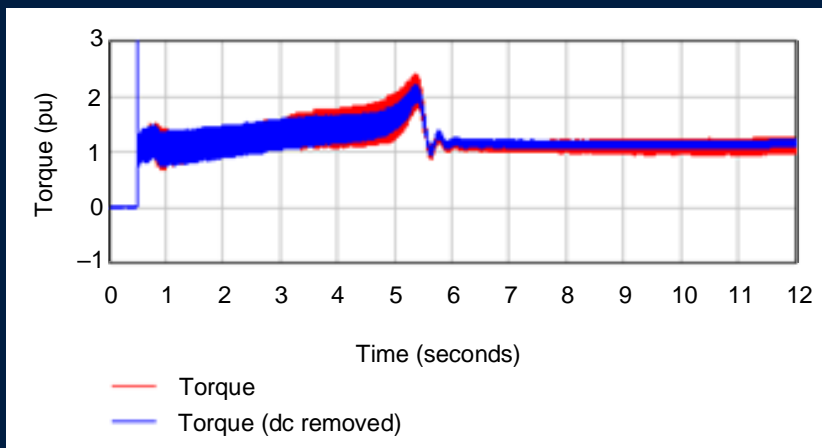
Oscillations in torque after motor is up to speed

DC in Voltages

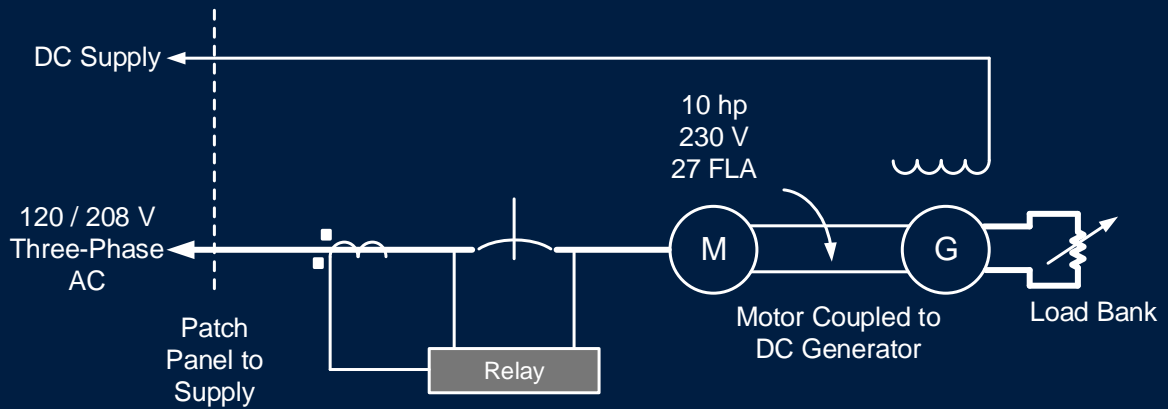


Linear decay in flux is indicator of dc in voltage

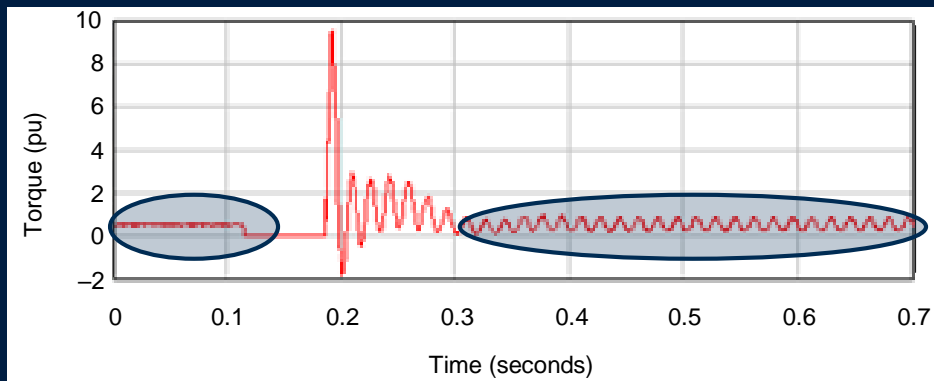
Torque After DC Removal



Example 2 – Motor Bus Transfer in Lab

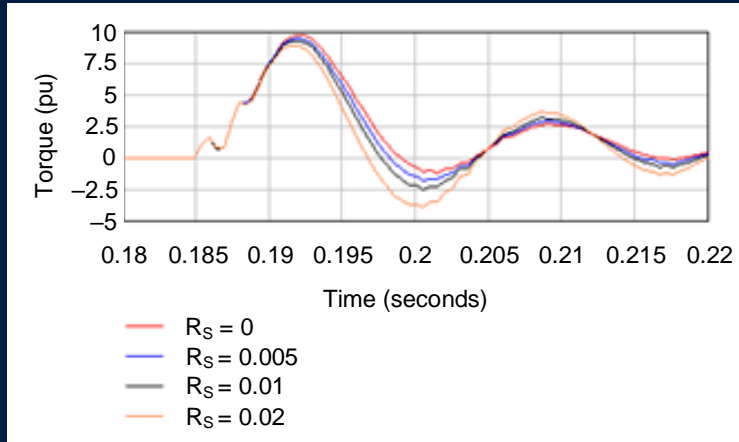


Torque for Transfer

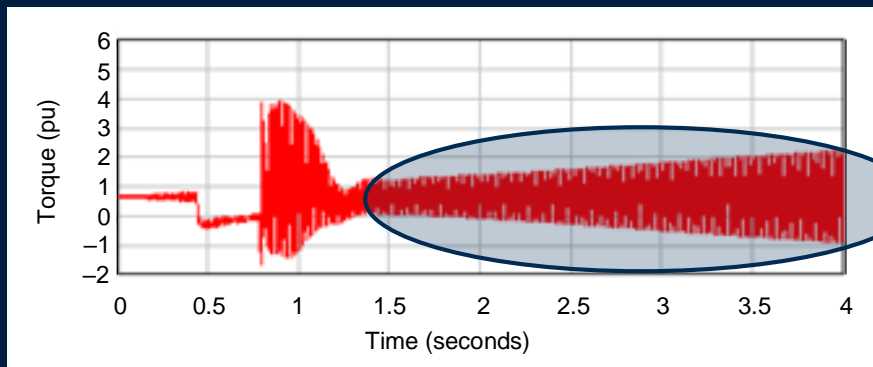


Good initialization with some oscillations

Torque With Stator Resistance Varied

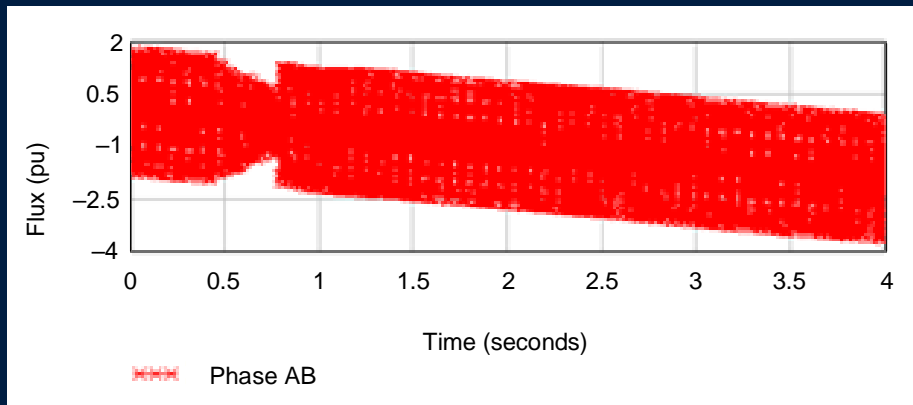


Example 3 – Real-World Motor Bus Transfer



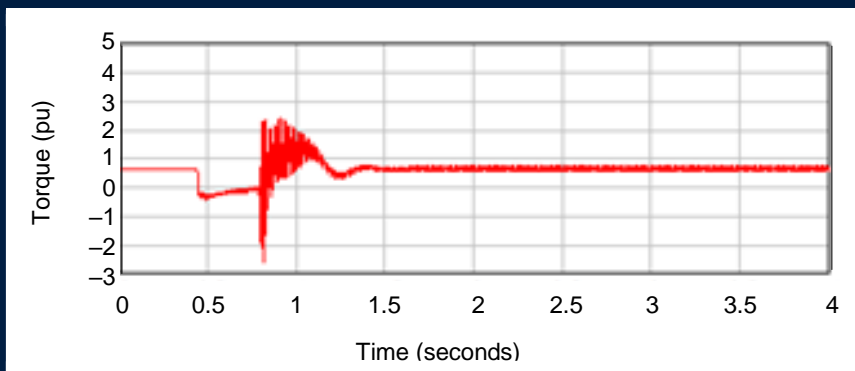
Increasing oscillations after transfer

DC in Voltages Once Again

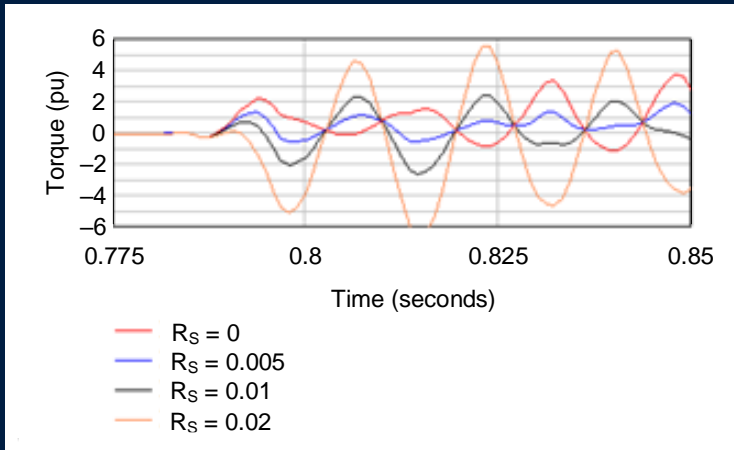


Linear decay in flux is indicator of dc in voltage

Torque After DC Removal

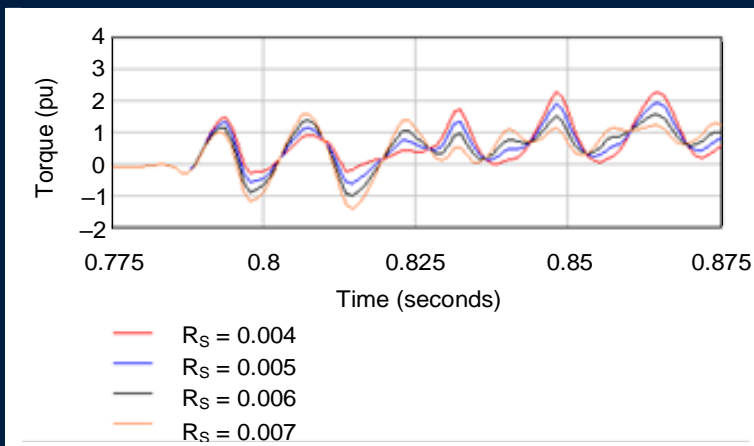


Torque vs. Stator Resistance



- Large variations in stator resistance impact torque calculation
- Refining estimate for RS helps

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Conclusions

- Torque calculation is based on validated measured electrical quantities
- Largest error sources are incorrect stator resistance and CT saturation

Questions