Automotive Application of an Advanced Power Conversion for Brushless Motor Control

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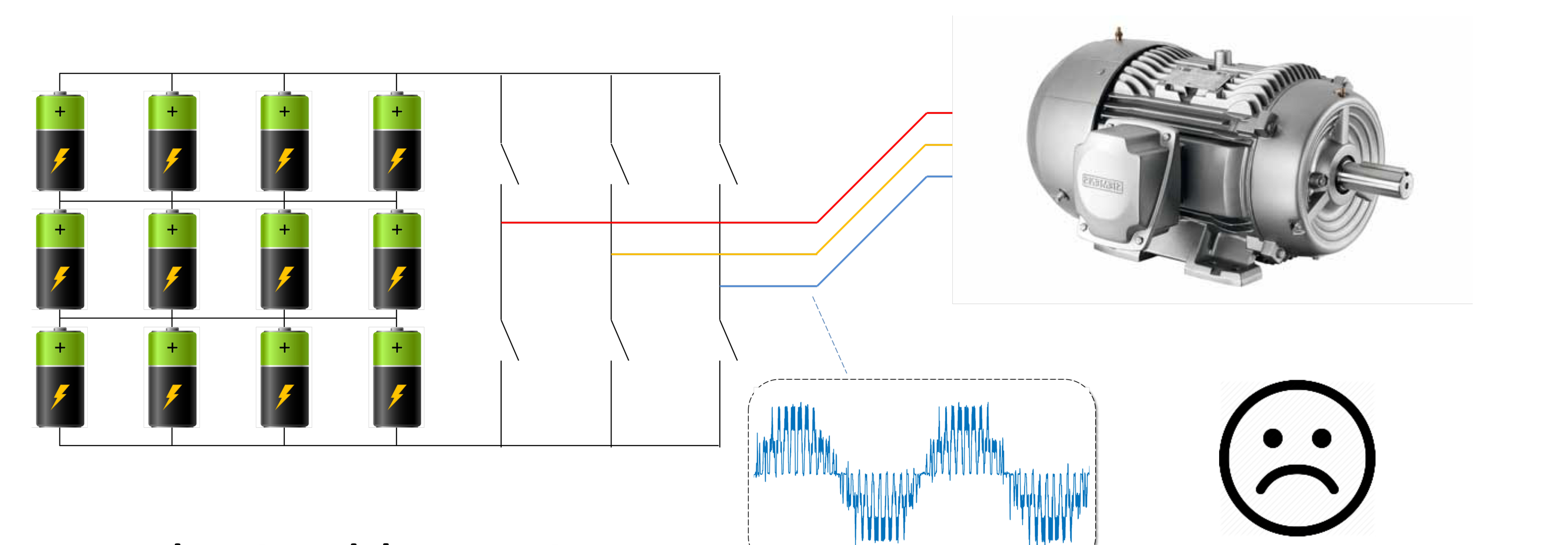
State of Art Electrical Vehicle and Problems



Hard-wired batteries

- *Bad fault-tolerance*
- *Needs complex battery management circuit*

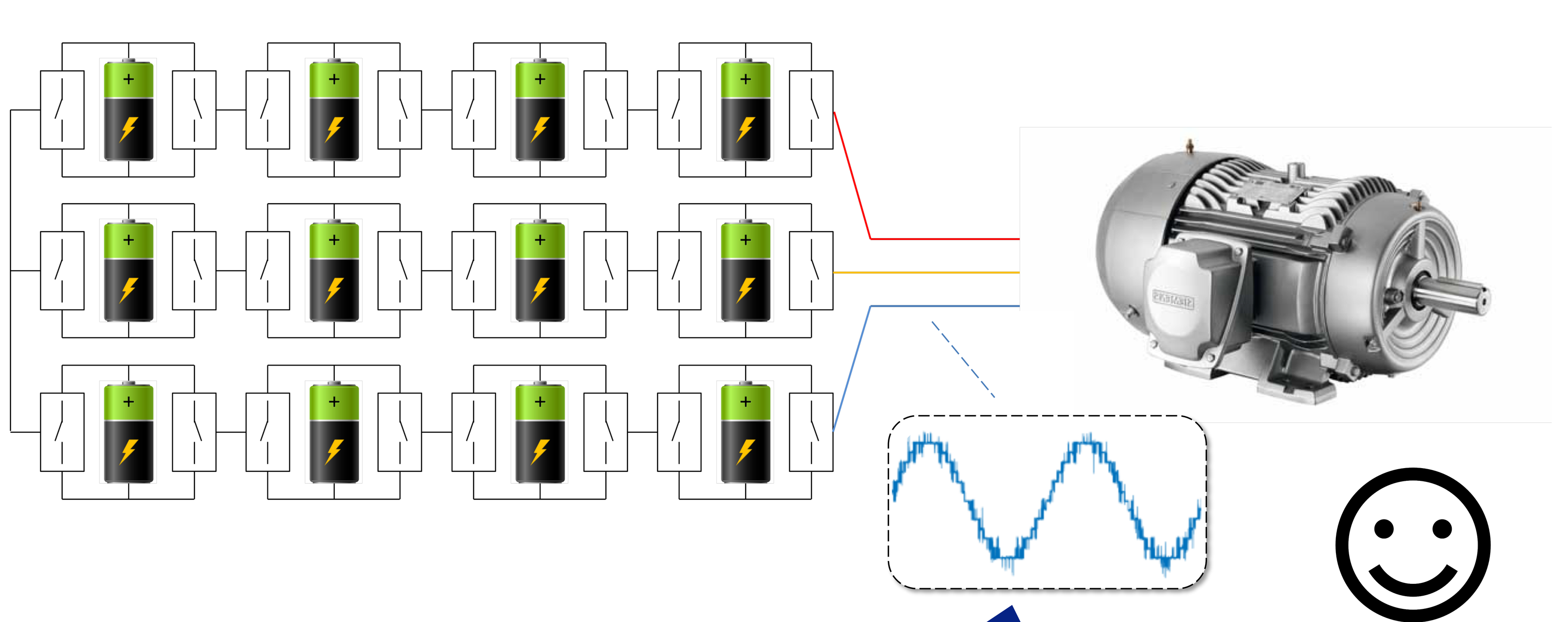
Controller

- *Output distortion*
- *Large EMI*

Motor

- *Large torque ripple*
- *Large noise*
- *Large insulation stress*

Our Solution : Intelligent Battery Modules

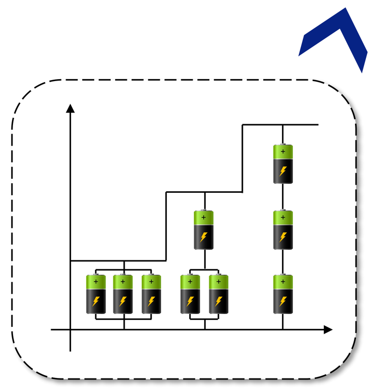


Modular batteries [1]

- *Battery interfaced by switches*

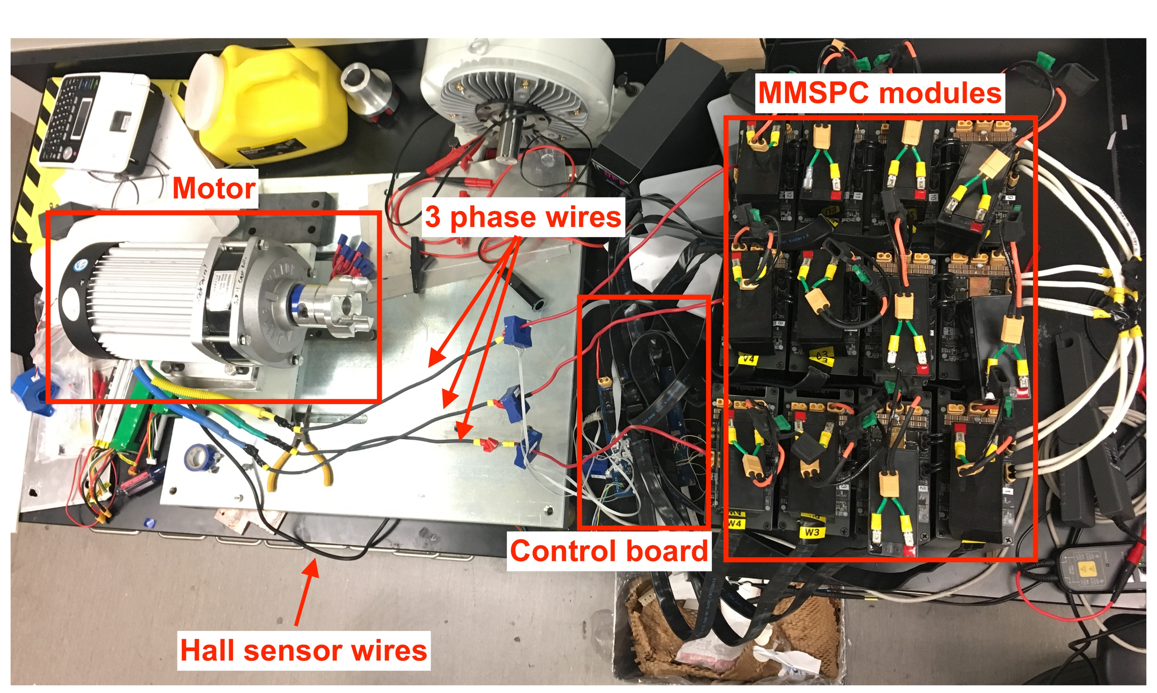
Smart control [2]

- *Sensor-less balancing*
- *Minimal losses*



- *High-quality output*
- *Less toque ripple*
- *Less insulation stress*
- *Great fault-tolerance*

System Test Setup



Intelligent battery module

Rotor Estimation from Hall Sensors

Field Oriented Control (FOC) requires continuous rotor angle estimation for Park and Inverse Park transforms.

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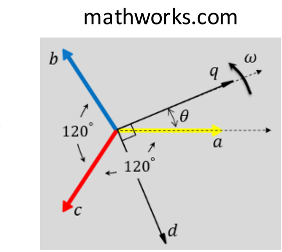


How should we sense rotor angle?

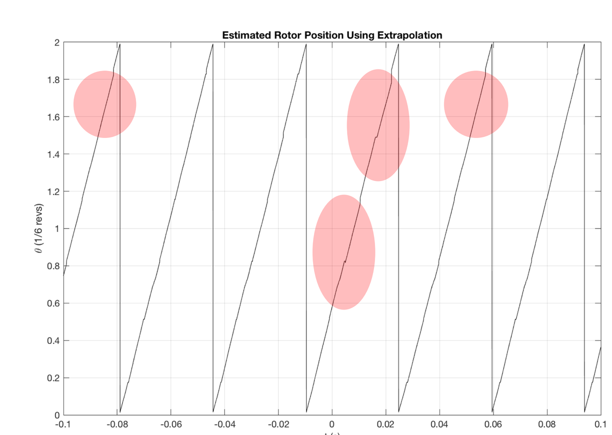
Sensor Method	Pros	Cons
Sensorless (back-emf)	• *Cheap* • *Works well at high speeds*	• *Reliance on software* • *Less precise/accurate*
Hall Sensors	• *Reasonably cheap* • *Fallback on trapezoidal* • *Robust hardware* • *Reliable control*	• *Must extrapolate from 60° increments* • *Subject to mechanical misalignment*
Encoder	• *Accurate and precise* • *No estimation required*	• *Expensive* • *Prone to hardware failure* • *Sensitive to poor installation*
Resolver	• *Most accurate/precise* • *No estimation required*	• *Most expensive* • *Interpretation of signal is nontrivial*

Two methods for continuous rotor angle estimation using hall sensors:

0th order Taylor extrapolation

- *Linear extrapolation from previous hall transition*
- *Estimate velocity with low-pass filter on hall transition intervals*

$$\hat{\theta}(t) = \theta_i + (t - t_i)\frac{\theta_i - \theta_{i-1}}{t_i - t_{i-1}}$$

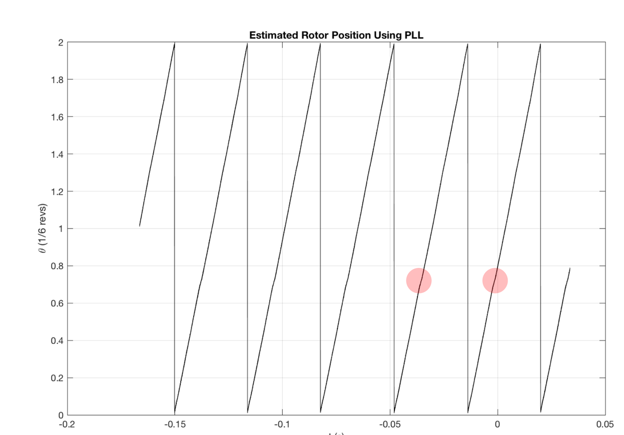


Phase Locked Loop (PLL)

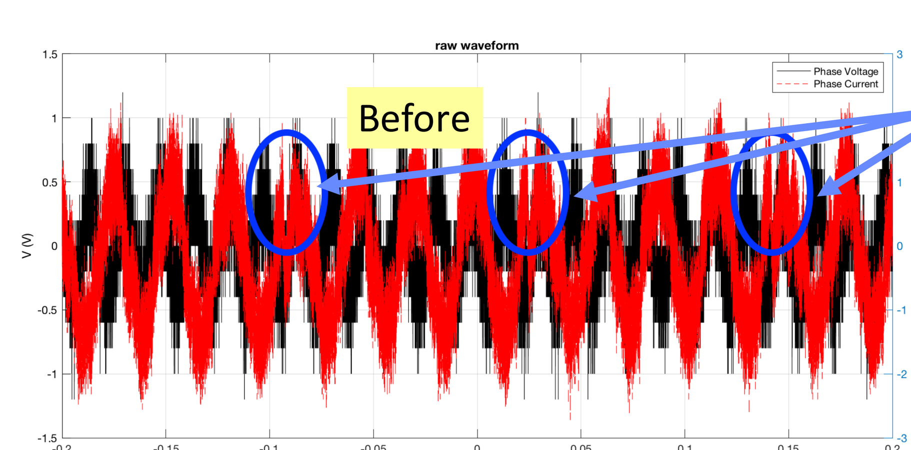
- *Apply PLL to lock onto hall transitions*
- *Single P controller on velocity to drive angle error to 0*

$$\hat{\theta}_j = \hat{\theta}_{j-1} + (t_j - t_{j-1})\left(\frac{\theta_i - \theta_{i-1}}{t_i - t_{i-1}} + u\right)$$

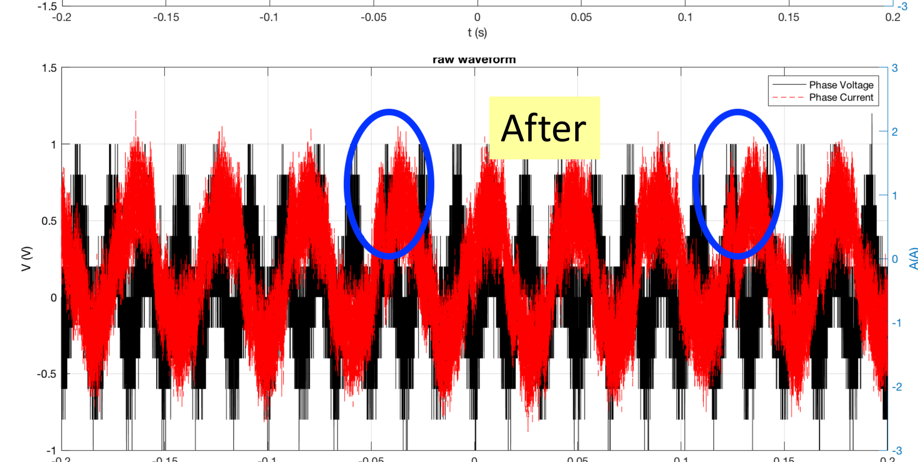
$$u = K(\theta_i - \hat{\theta}_i)$$



Hall Sensor Calibration



Small errors in angle estimation cause large spikes in motor phase current waveform.



Pre-calibrate hall sensor misalignment:

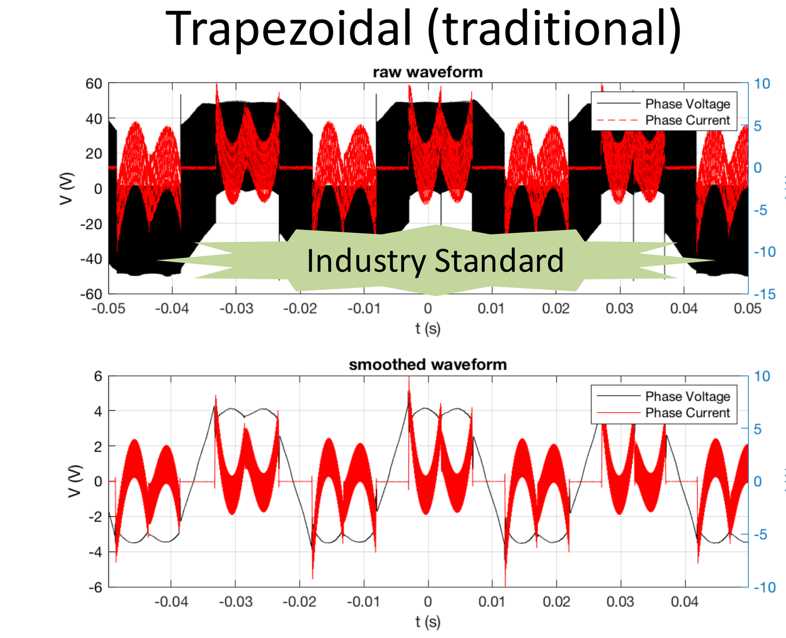
Run motor in open loop at constant speed and measure hall sensor timing.
Storing one electrical revolution is insufficient since there are 4 pole pairs: must store 4 revolutions (24 transition times).

Motor Control

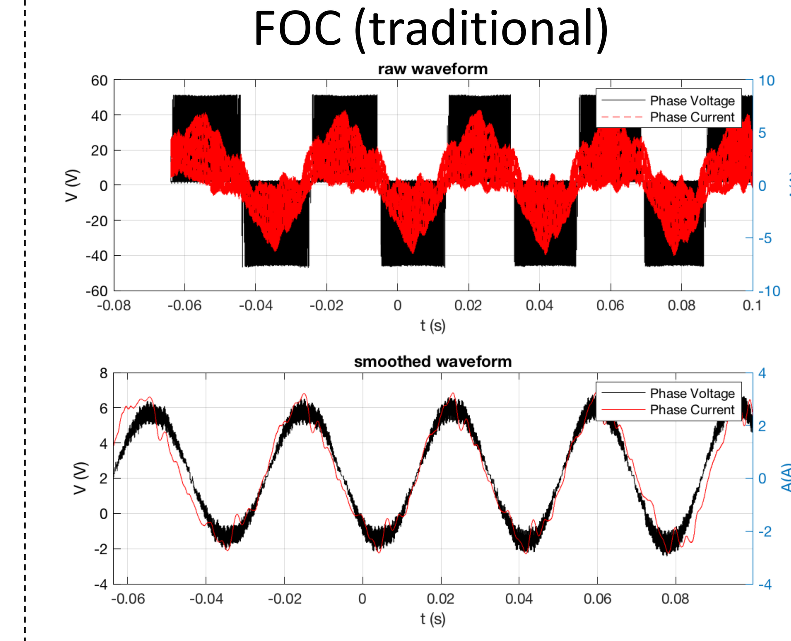
Table 1: MMSPC Motor Control Comparison

Control Scheme	Trapezoidal MMSPC	Trapezoidal traditional	FOC extrapolation MMSPC	FOC extrapolation traditional	FOC PLL MMSPC	FOC PLL traditional
Average Current (Arms)	2.170	2.438	1.587	2.165	$\boxed{1.495}$	2.305
Noise (Arms)	2.412	2.964	0.995	2.086	$\boxed{0.941}$	2.086

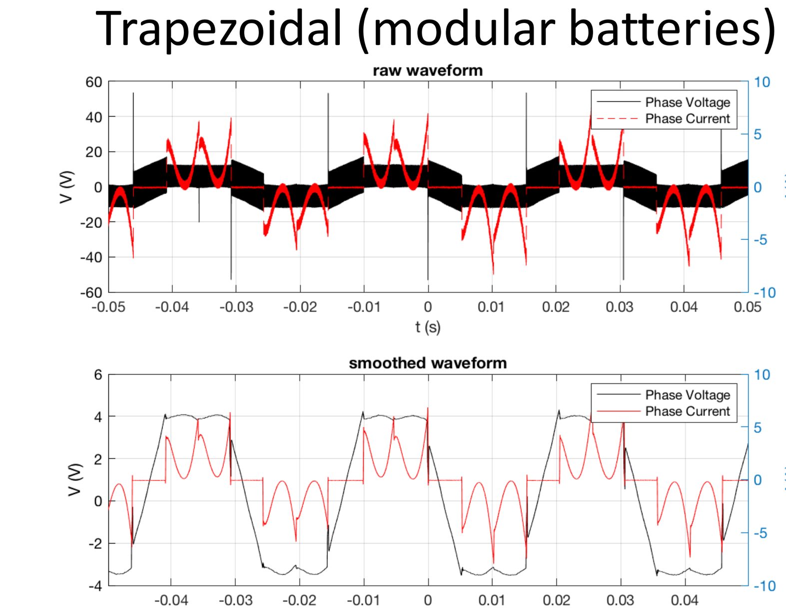
Trapezoidal (traditional)



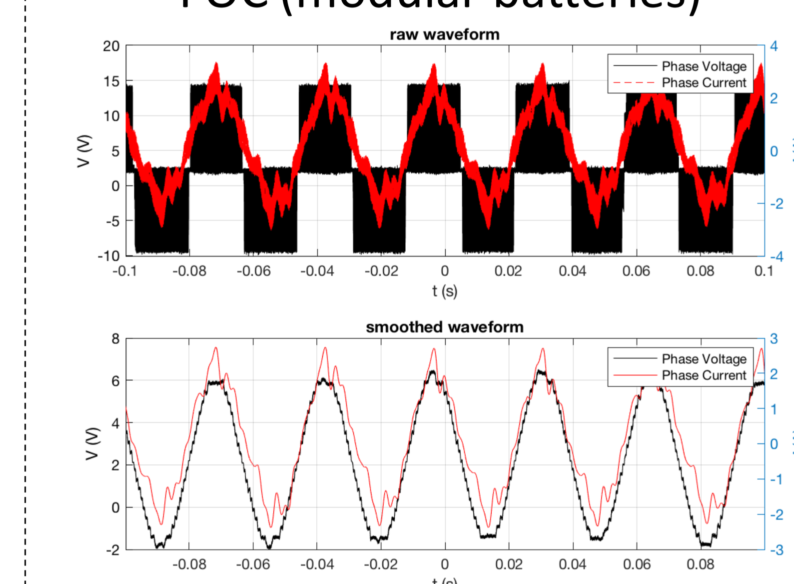
FOC (traditional)



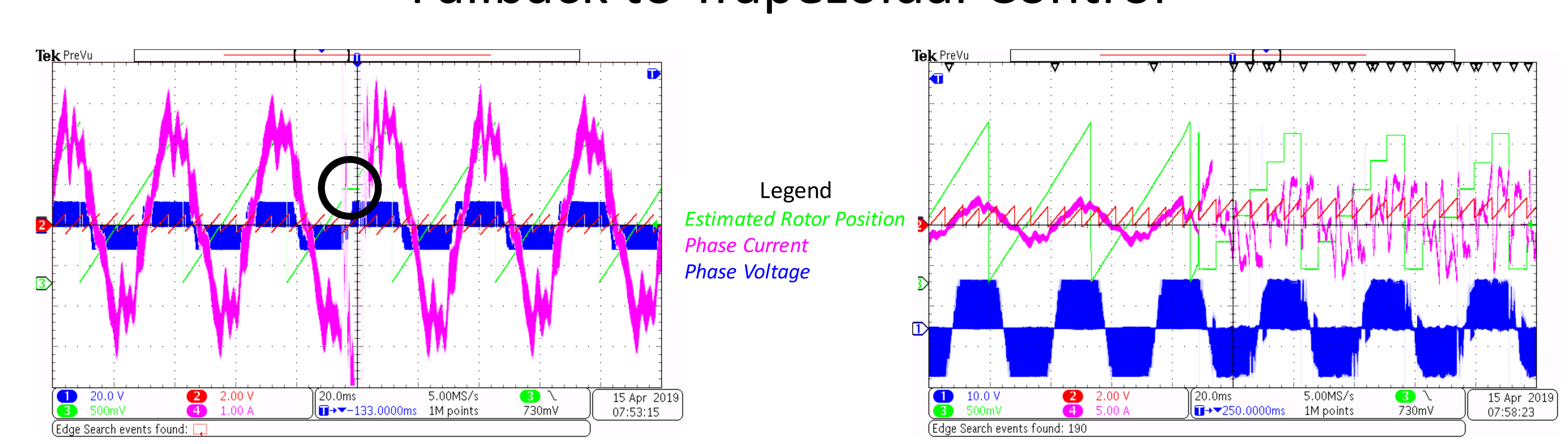
Trapezoidal (modular batteries)



FOC (modular batteries)



Fallback to Trapezoidal Control



Future Work

- *Remake module mounting array with aluminum base*
- *Mount the system on our test vehicle*
- *Test for auditory noise, torque responsiveness, winding temperature, and electrical-to-mechanical efficiency*

References

[1] Goetz, Stefan M., et al. "Control of Modular Multilevel Converter With Parallel Connectivity—Application to Battery Systems." IEEE Transctions on Power Electronics 32.11 (2017): 8381-8392.

[2] Z. Li, A. V. Peterchev, R. Lizana, and S. M. Goetz, "Distributed Balancing Control for Modular Multilevel Series/Parallel Converter with Capability of Sensor-less Operation," in Energy Conversion Congress and Exposition (ECCE), 2017 IEEE, 2017.