Automotive Application of an Advanced Power Conversion for Brushless Motor Control

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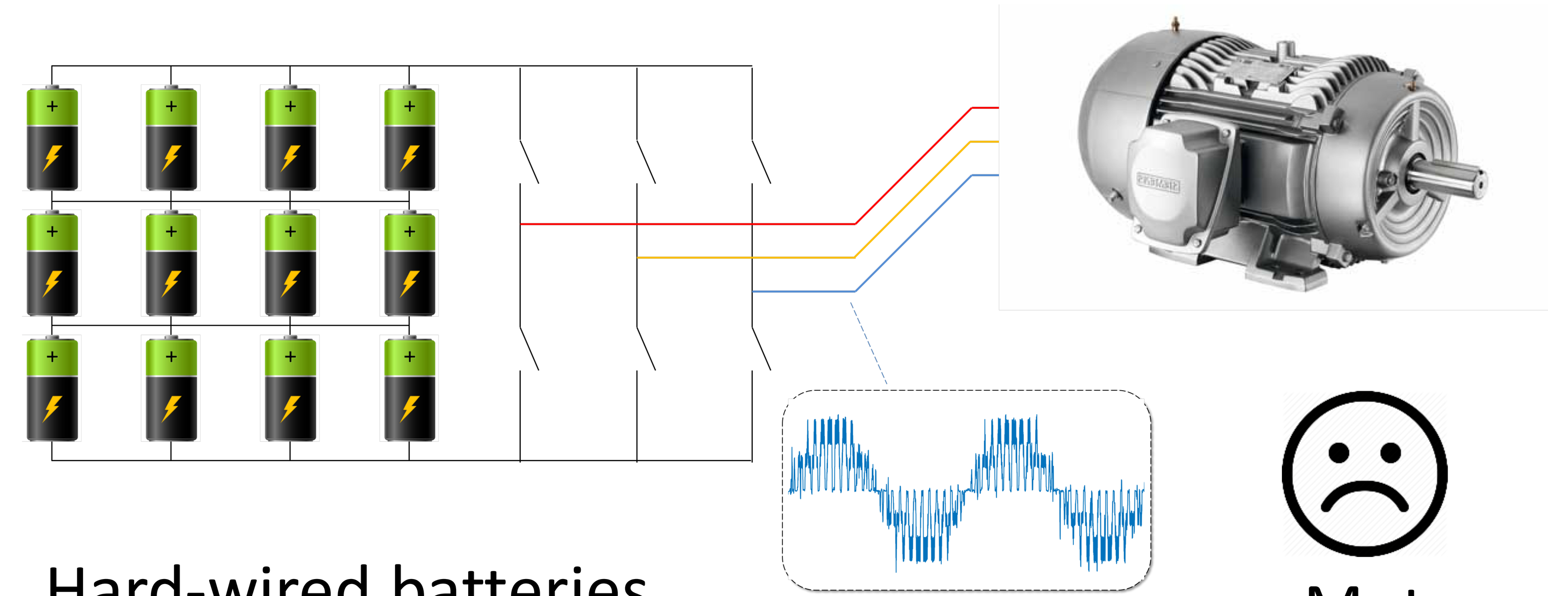
State of Art Electrical Vehicle and Problems

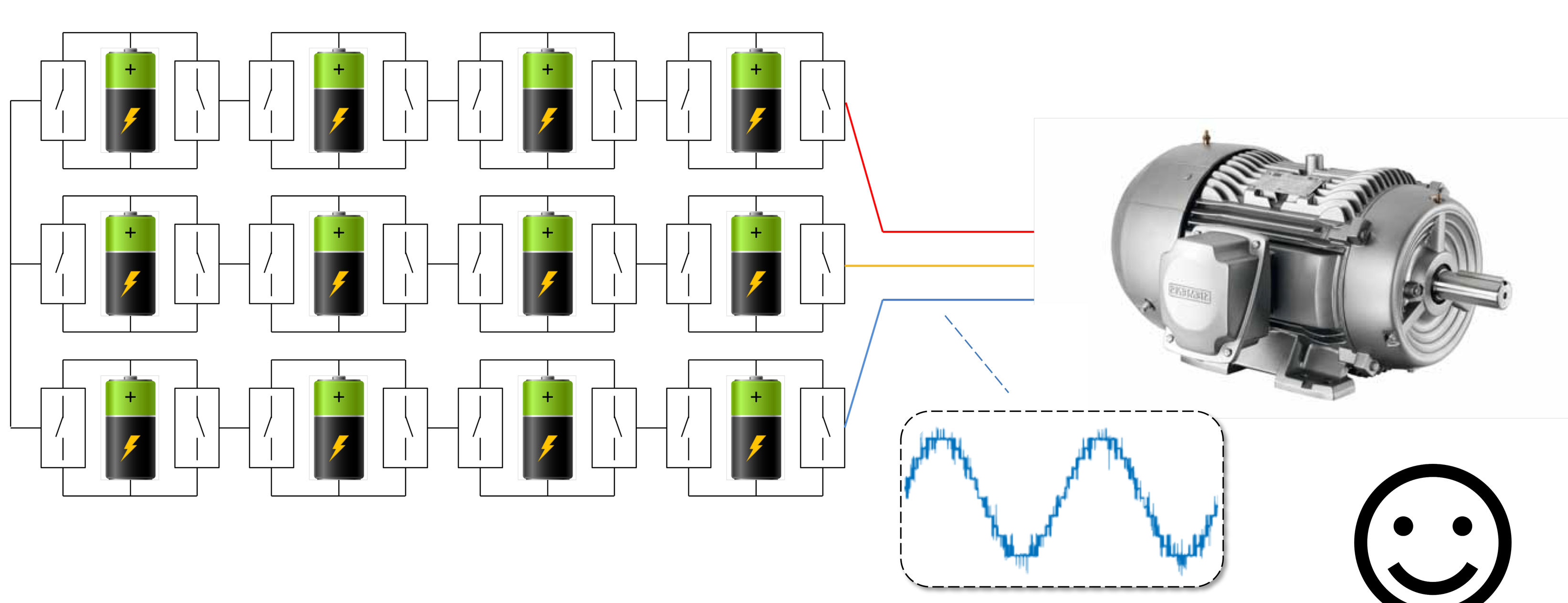


Hard-wired batteries
- *Bad fault-tolerance*
- *Needs complex battery management circuit*

Controller
- *Output distortion*
- *Large EMI*

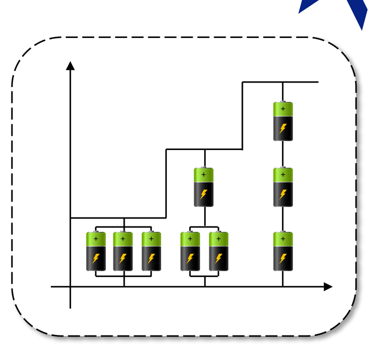
Motor
- *Large torque ripple*
- *Large noise*
- *Large insulation stress*

Our Solution : Intelligent Battery Modules



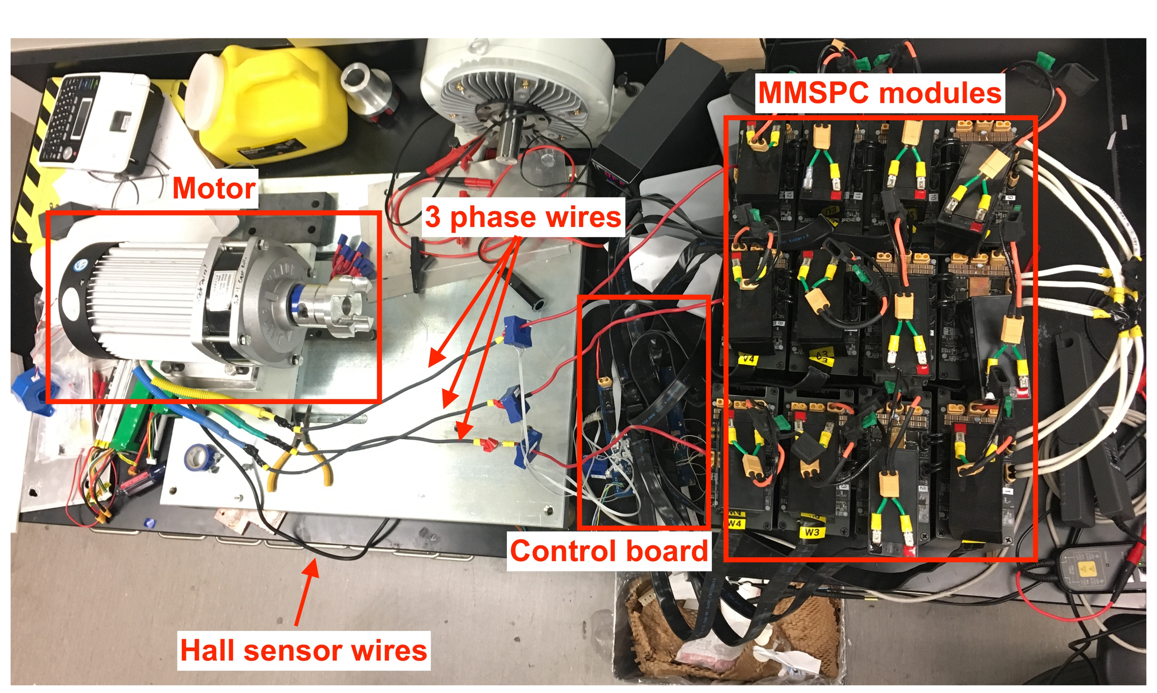
Modular batteries [1]
- *Battery interfaced by switches*

Smart control [2]
- *Sensor-less balancing*
- *Minimal losses*



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

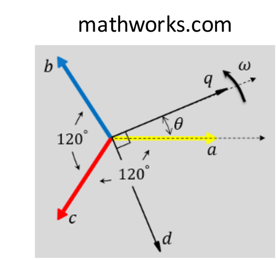
System Test Setup



Intelligent battery module

Rotor Estimation from Hall Sensors

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



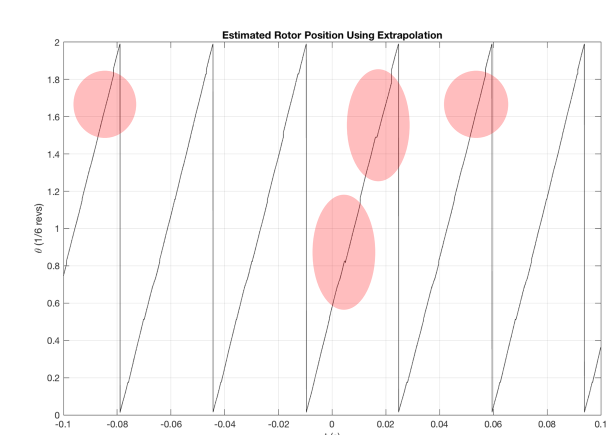
How should we sense rotor angle?

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*

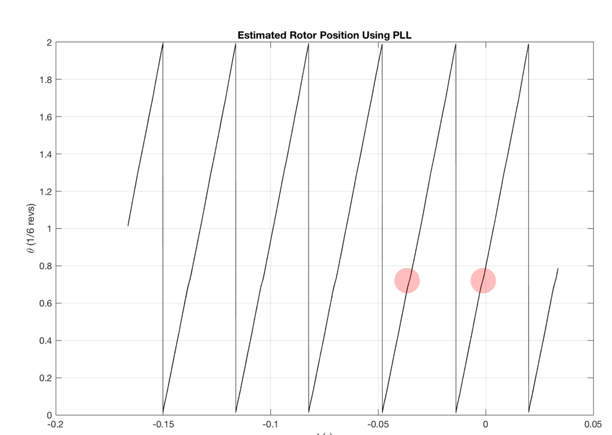
$$\hat{\theta}(t) = \theta_i + (t - t_i)\frac{\theta_i - \theta_{i-1}}{t_i - t_{i-1}}$$



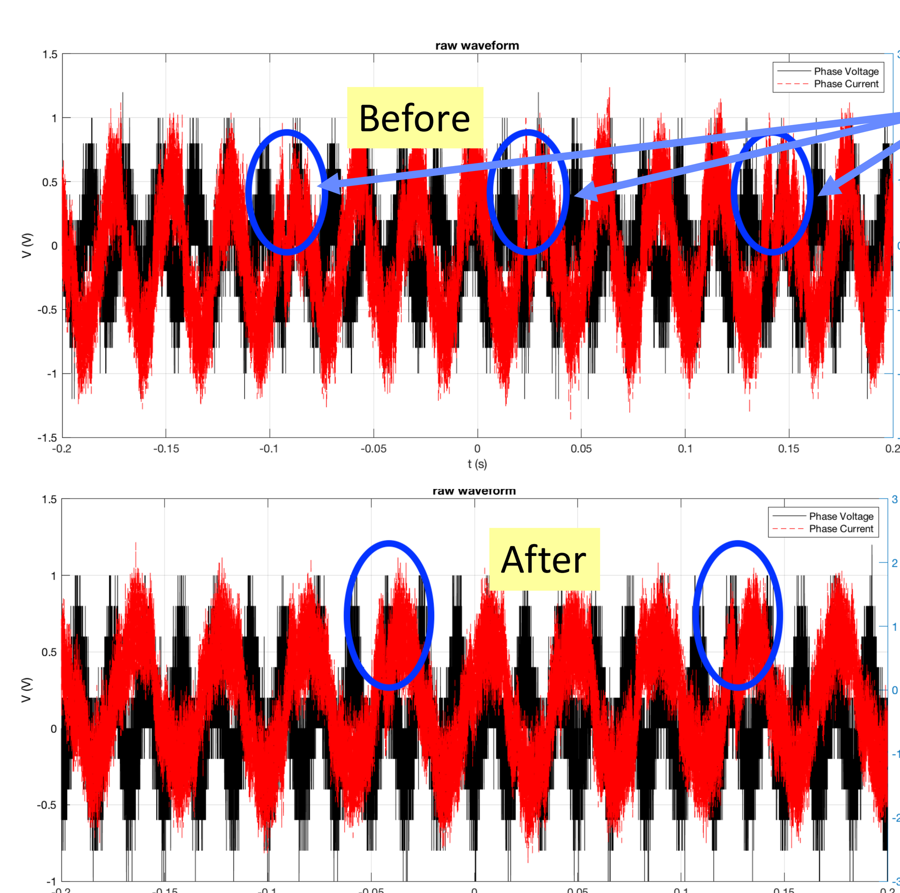
Phase Locked Loop (PLL)
- *Apply PLL to lock onto hall transitions*
- *Single P controller on velocity to drive angle error to 0*

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

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



Hall Sensor Calibration



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

Pre-calibrate hall sensor misalignment:

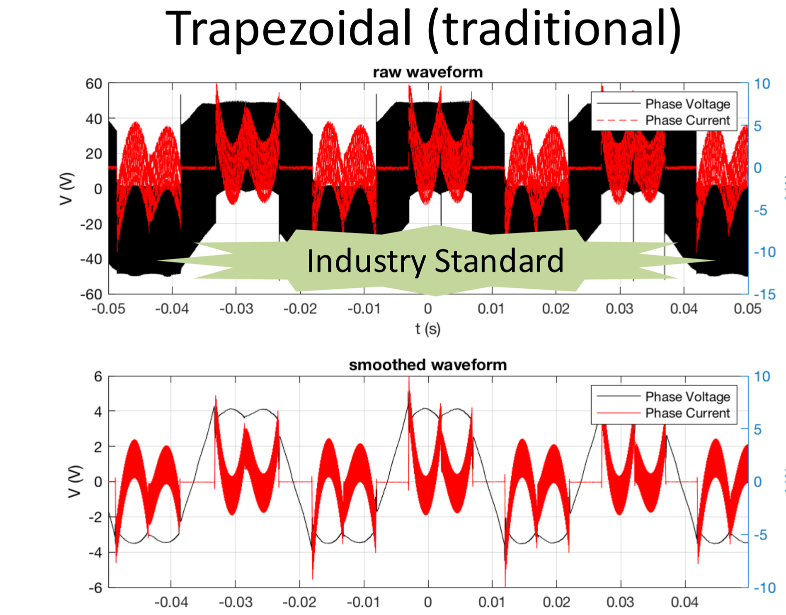
Run motor in open loop at constant speed and measure hall sensor timing.
Storing one electrical revolution is insufficient since there are 4 pole pairs: must store 4 revolutions (24 transition times).

Motor Control

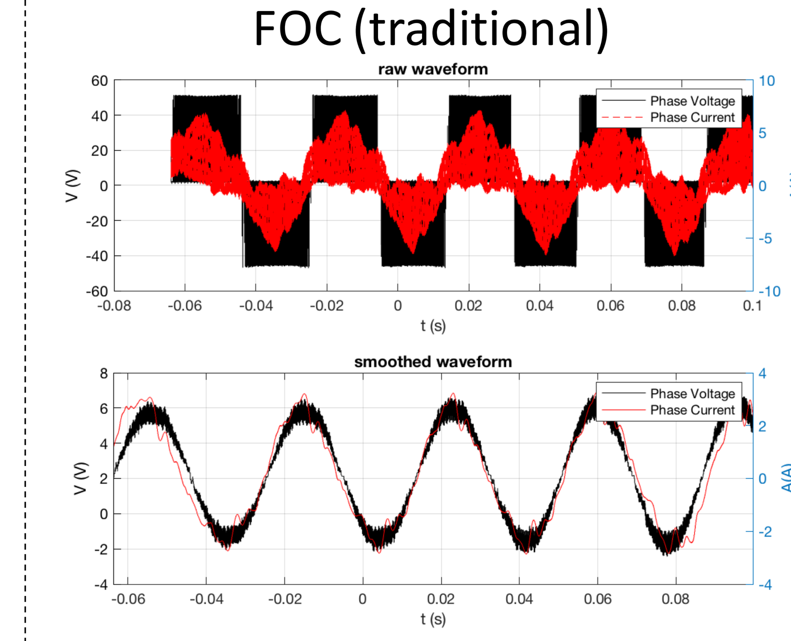
Table 1: MMSPC Motor Control Comparison

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

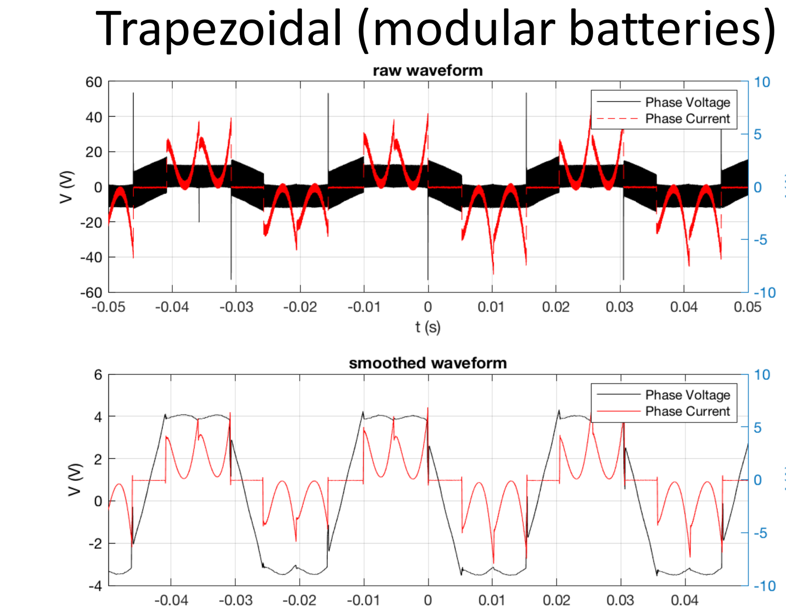
Trapezoidal (traditional)



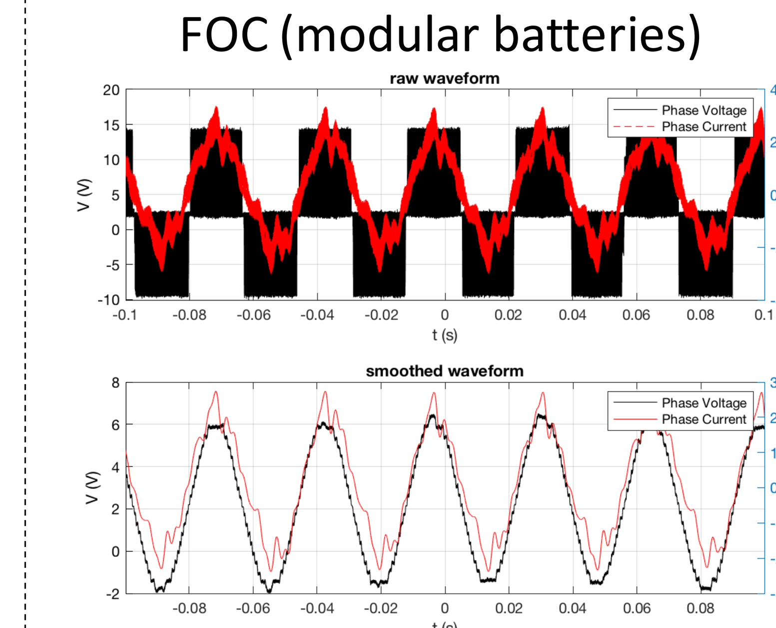
FOC (traditional)



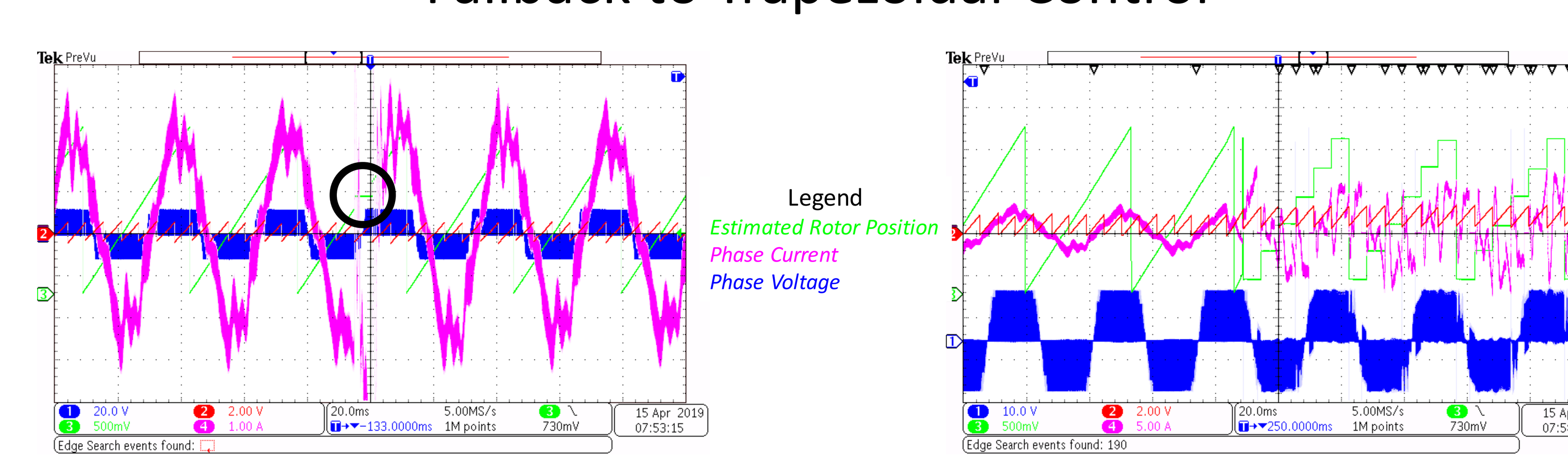
Trapezoidal (modular batteries)



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.