An Electric Vehicle with Novel Powertrain

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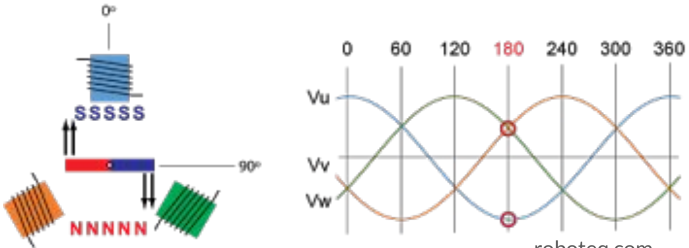
Overview



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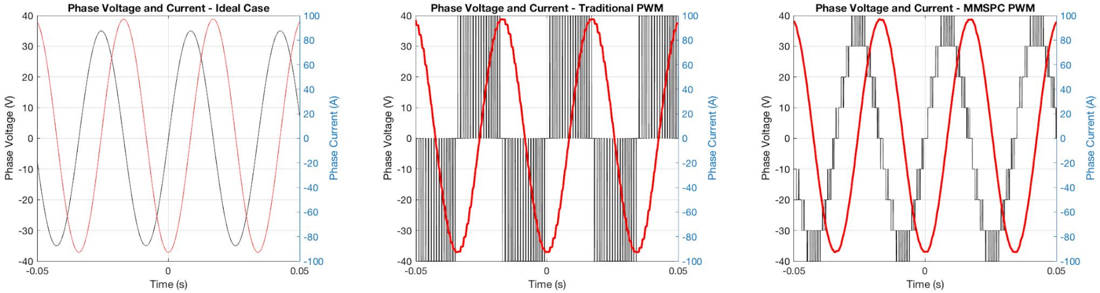
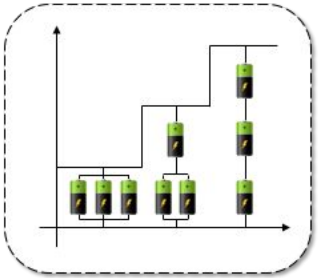
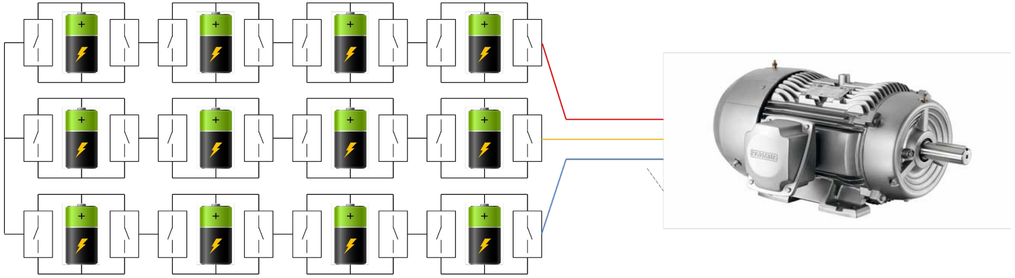
- BLDC motors are the most common type used in electric vehicle propulsion
- Motor control requires sinusoidal voltage to produce sinusoidal current
- SoA: Field Oriented Control (FOC) using PWM
- Our contribution: modular battery system to create smoother sinusoidal waveforms



Modular Multilevel Series-Parallel Converter (MMSPC)

- Dynamically reconfigure battery modules in series or in parallel
- Reduces switching losses, noise, and stress
- Modularity facilitates assembly and repair while reducing cost

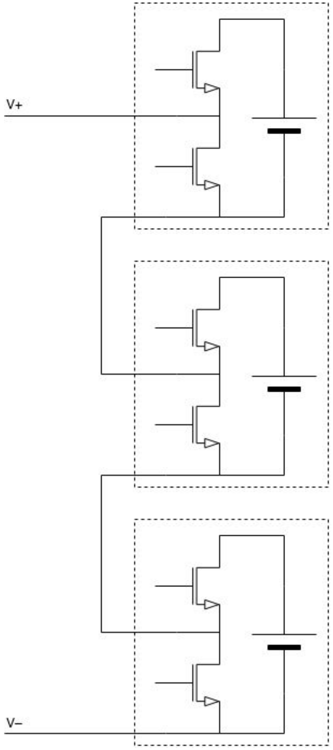




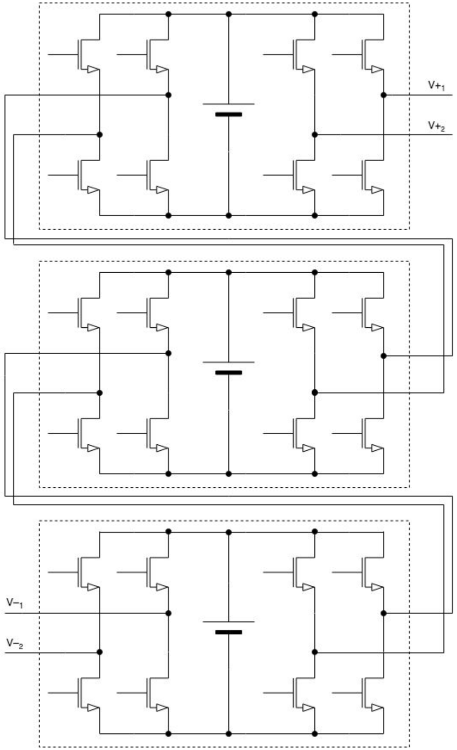
MMSPC (cont)

- Limited work done on modular (non-parallel) battery systems (MMC) for AC motor control [1]
- MMSPC enables modules to be connected in parallel:
  - Sensorless balancing
  - Equivalent semiconductor area as comparable MMC topology (full bridge)

MMC
(half-bridge topology)



MMSPC
(ours)

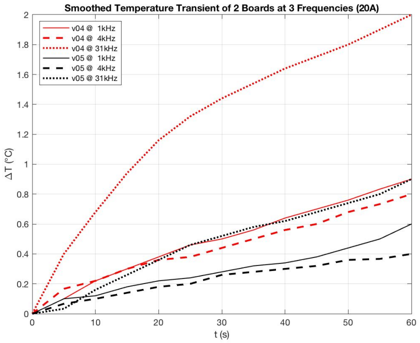


[1] M. Hagiwara, K. Nishimura and H. Akagi, "A Medium-Voltage Motor Drive With a Modular Multilevel PWM Inverter," in *IEEE Transactions on Power Electronics*, vol. 25, no. 7, pp. 1786-1799, July 2010. doi: 10.1109/TPEL.2010.2042303

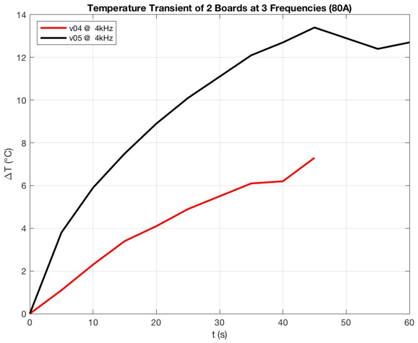
MOSFET Selection and Thermal Considerations

- Modeling MOSFET switching losses can be difficult - use thermal analysis to compare losses
- Compare two MOSFETs: higher $R_{DS,on}$ vs higher C_g to view relative importance of switching losses
- Switching losses account for approximately 13% of losses
- MOSFET case only ~11°C above ambient @ 80A

Switching Losses

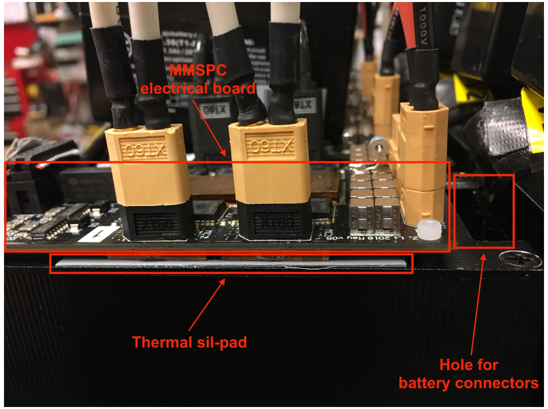


Conduction Losses



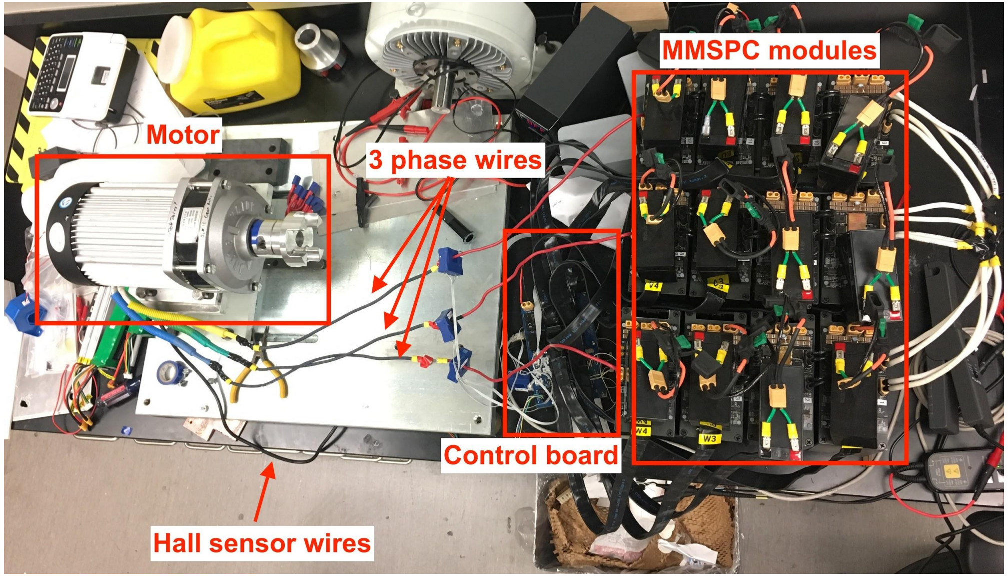
MMSPC Module Mechanical Design

- Module must:
  - Be sturdy and vibration resistant
  - Hold batteries and board
  - Be easy to mount and unmount
  - Dissipate battery and board heat
- Extruded aluminum boxes chosen
- Slots CNC milled to accommodate wiring to batteries
- Electronics board mounted with screws and sil-pad



System Setup

- NI sbRIO-9627 control board + custom motherboard
- BM1424ZXF-2.2KW72V motor
- 12 MMSPC modules

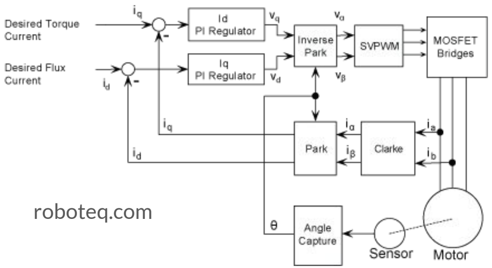


Motor Control - Introduction

- Control schemes:
  - Trapezoidal control (easiest, standard in low power applications)
  - Sinusoidal control
  - Field Oriented Control (FOC) (Industrial/Automotive standard)
    - FOC requires continuous rotor angle estimation

- Sensor types:
  - Sensorless (back-emf)
  - Hall Sensors
  - Encoder
  - Resolver

FOC block diagram



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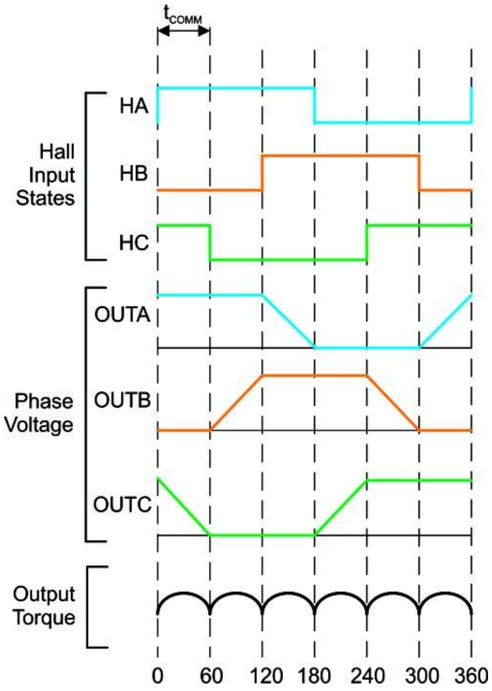
Trapezoidal waveforms



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Rotor Angle Estimation

- Hall sensors have many advantages:
  - Reliable
  - Inexpensive
  - Ubiquitous
  - Simple control
- Downside: only provide 60° resolution - must extrapolate rotor position

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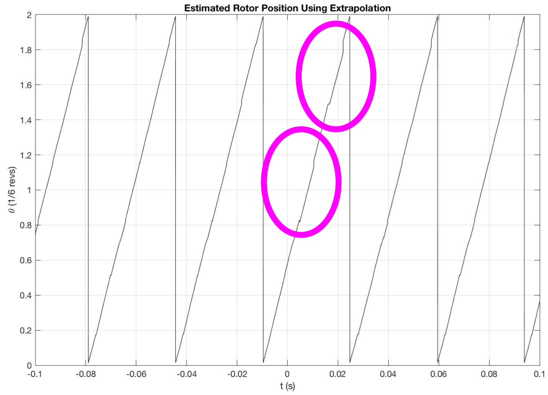
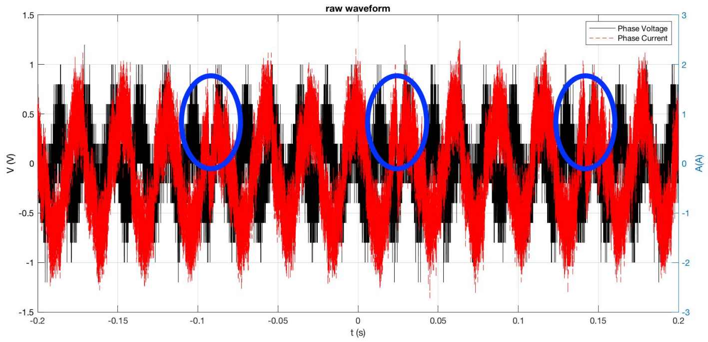
Rotor Angle Estimation (cont)

First approach: 0th order Taylor extrapolation

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

Problem: susceptible to sensor misalignment



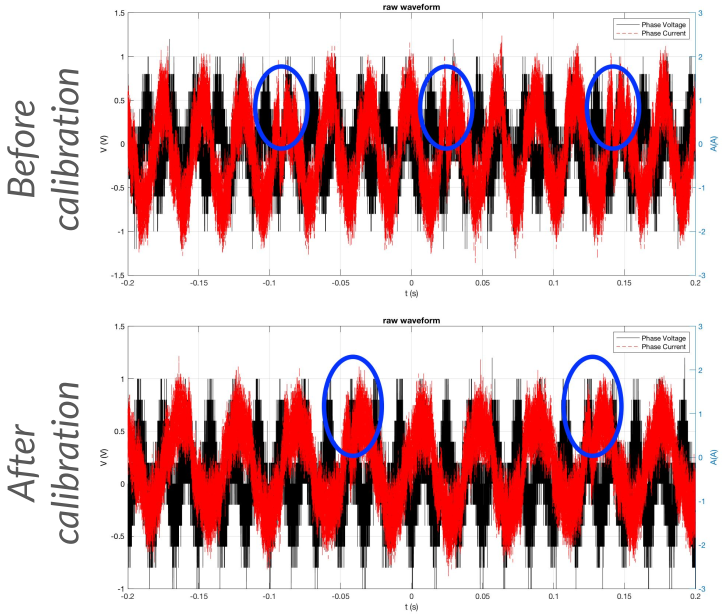


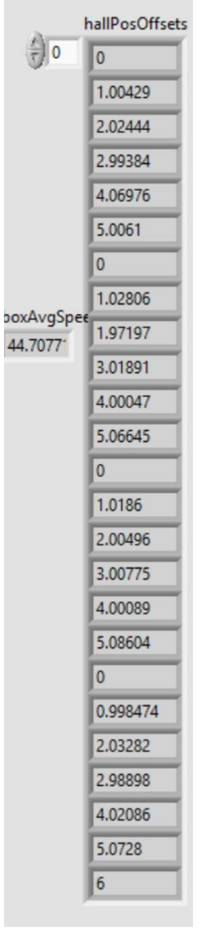
Rotor Angle Estimation (cont)

Refinement: Hall sensor misalignment calibration

Idea: store measured locations of hall sensors during open-loop control

Result: minor improvements





Rotor Angle Estimation (cont)

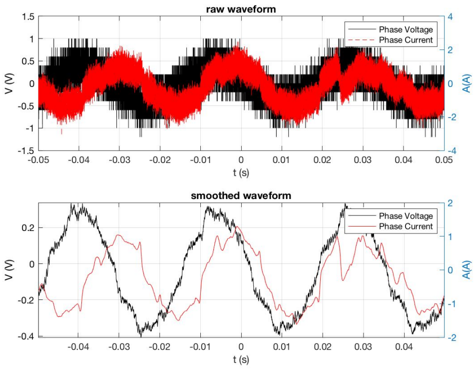
New approach: Phase Locked Loop (PLL) on rotor angle

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

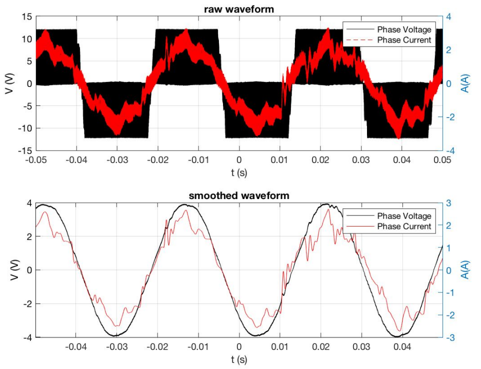
$$u = K(\theta_i - \hat{\theta}_i)$$

Idea: guarantees continuous position + velocity

Extrapolation before calibration

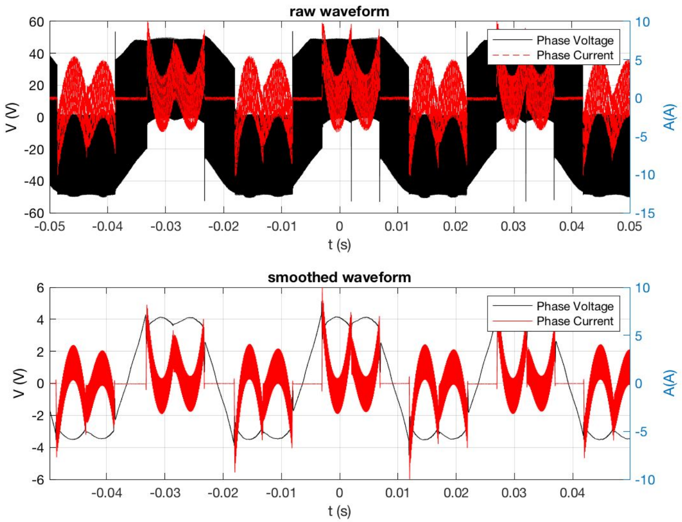


PLL after calibration

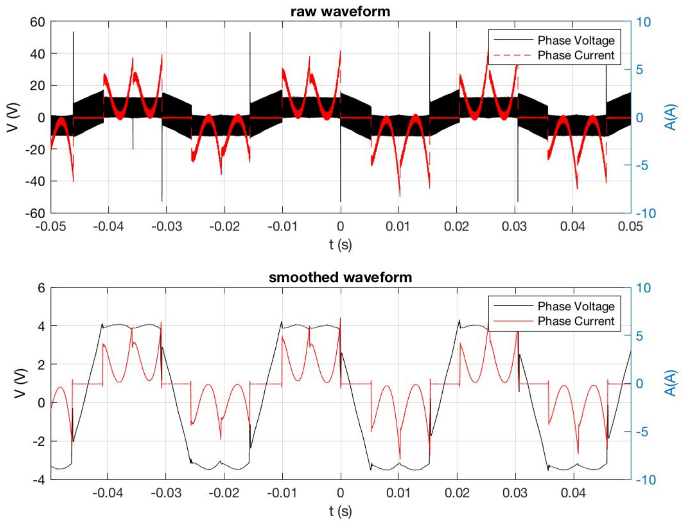


MMSPC: Trapezoidal (control)

Without MMSPC

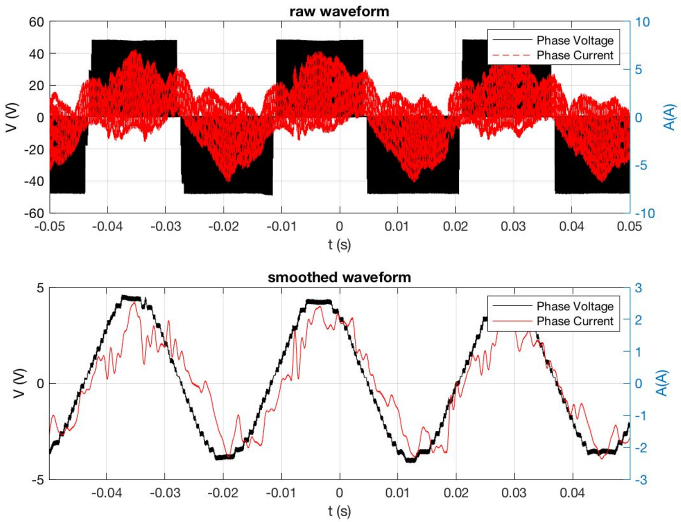


With MMSPC

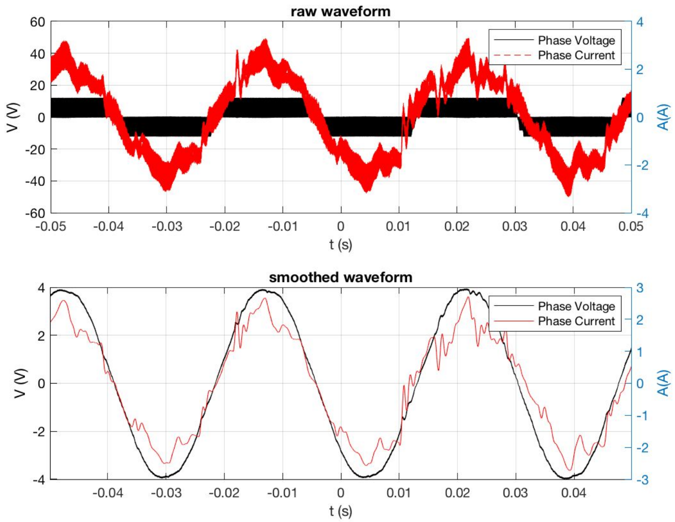


MMSPC: FOC - Extrapolated Rotor Angle

Without MMSPC

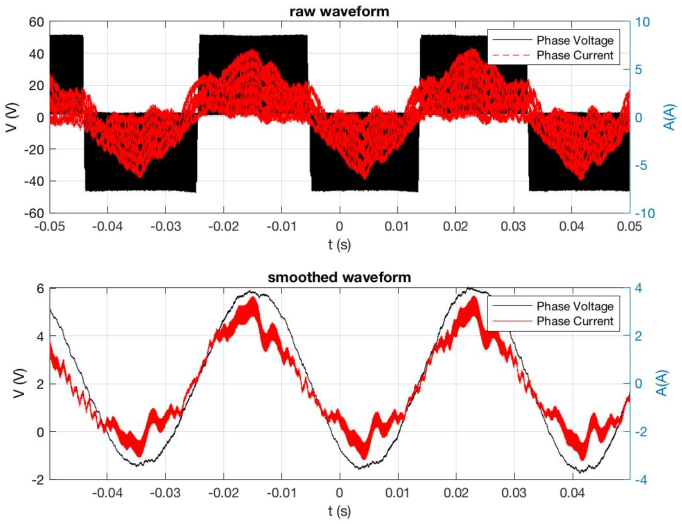


With MMSPC

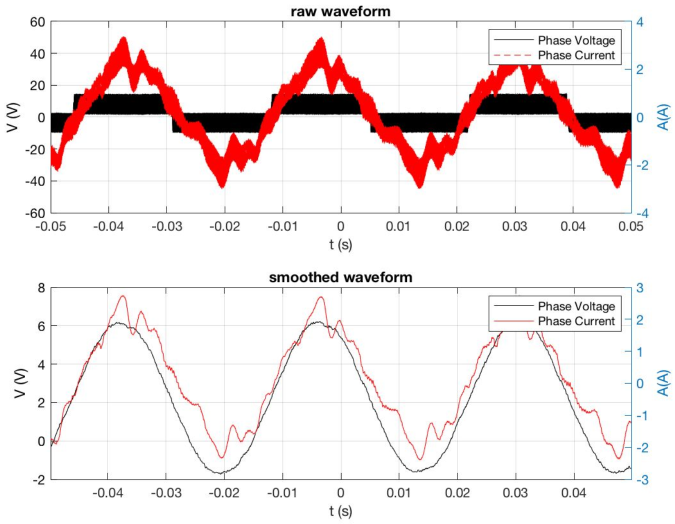


MMSPC: FOC - PLL Rotor Angle

Without MMSPC



With MMSPC



Motor Control: Comparison

- **MMSPC** *outperforms* traditional PWM in every control scheme and both metrics
- **FOC** *outperforms* trapezoidal in both metrics and PWM schemes
- **PLL** *outperforms* 0th order Taylor extrapolation in both metrics and PWM schemes

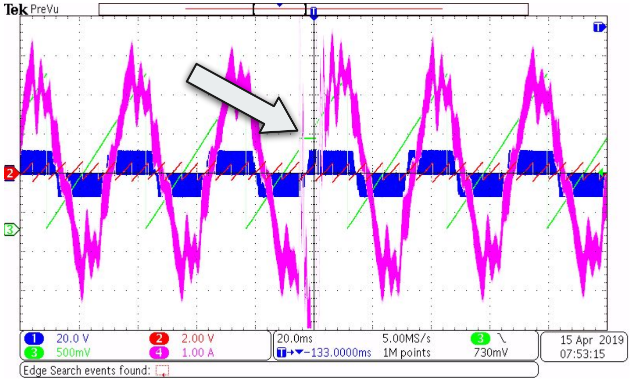
Table 1: MMSPC Motor Control Comparison

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

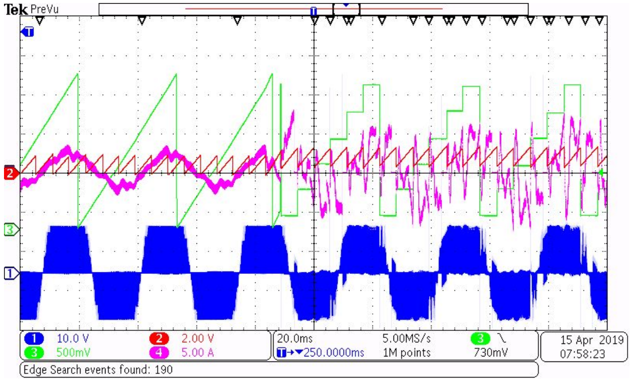
Motor Control: Fallback to trapezoidal

Hall sensors can revert to trapezoidal control in the event of total software failure or when PLL loses lock

Momentary PLL loss



Extended PLL loss



Conclusions

- An MMSPC system for motor control was constructed with sufficient heat dissipation and structural integrity.
- Continuous rotor angle estimation can be successfully achieved with a PLL and misalignment calibration.
- MMSPC modulation is superior to traditional PWM for every control scheme when comparing current consumption and noise.
- FOC PLL fallback to trapezoidal control was demonstrated to maintain safe, stable control of the motor.

Next Steps

- Install the system on a dune-buggy to stress-test in real-world conditions
- Perform rigorous analyses of:
  - Power consumption
  - Power factor
  - Auditory noise
  - Torque ripple
  - Battery stress
  - Battery balancing

Thank you. Questions?