FREEDM SYSTEMS CENTER Research Symposium 2023

PMSM Control Strategies in Consideration of Machine Nonidealities

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Outline

- Research Background and Objectives
- Nonideal PMSM Model
- Harmonic Identification of Back-EMF
- Current Control Strategies of PMSMs with Non-sinusoidal Back-EMF
- Impact on Power Loss
- Impact on Extended Back-EMF Based Position Sensorless Control
- Research Opportunities

Research Background and Objectives

▪ Non-idealities in PMSMs

– A limited number of stator and rotor core slots result in non-uniform air-gap lengths causing machine parameters to have harmonic components [1]

– Non-uniform magnetic saturation causes cross-coupling of inductance between *d*- and *q*-axes and varying magnet flux linkage with motor current [2]

– Nonideal characteristics become severe in low-cost or medium voltage motor applications with full-pitch and concentric coils

▪ Related Research Topic

1. Torque ripple reduction (Low speed)

- Optimal design of the stator and rotor [3]-[5]
- Optimal current reference and its control [6]-[10]

2. Harmonic loss reduction control [8]

3. Position sensorless control

Research Background and Objectives

- **Objectives**
  - Experimental identification of machine non-idealities
  - Sinusoidal current control scheme
    1) Efficiency improvement
    2) Improvement in angle estimation performance in EEMF based sensorless control

Nonideal PMSM Model

Nonideal IPMSM Model

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds}(\theta_r) - \omega\lambda_{qs}(\theta_r)$$

$$\lambda_{ds}(\theta_r) = L_d(\theta_r)\, i_{ds} + L_{dq}(\theta_r)\, i_{qs} + \lambda_{dPM}(\theta_r)$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs}(\theta_r) + \omega\lambda_{ds}(\theta_r)$$

$$\lambda_{qs}(\theta_r) = L_q(\theta_r)\, i_{qs} + L_{qd}(\theta_r)\, i_{ds} + \lambda_{qPM}(\theta_r)$$

$$L_d(\theta_r) = L_{d0} + L_{d6} cos 6\theta_r + L_{d12} cos 12\theta_r + \cdots$$

$$L_{dq}(\theta_r) = L_{dq0} + L_{dq6} sin 6\theta_r + L_{dq12} sin 12\theta_r + \cdots$$

$$L_q(\theta_r) = L_{q0} + L_{q6} cos 6\theta_r + L_{q12} cos 12\theta_r + \cdots$$

$$L_{qd}(\theta_r) = L_{qd0} + L_{qd6} sin 6\theta_r + L_{qd12} sin 12\theta_r + \cdots$$

$$\lambda_{dPM}(\theta_r) = \lambda_{dPM.0} + \lambda_{dPM.6} cos 6\theta_r + \lambda_{dPM.12} cos 12\theta_r \cdots$$

$$\lambda_{qPM}(\theta_r) = \lambda_{qPM.0} + \lambda_{qPM.6} sin 6\theta_r + \lambda_{qPM.12} sin 12\theta_r \cdots$$

- The triplen harmonics are absent in a *Y*-connected balanced 3-phase circuit
- Other harmonics in order of $(6n\pm1)$ in abc frame are presented as multiples of 6^{th} order harmonics in SRF

Nonideal PMSM Model

- **Simplified Nonideal IPMSM Model**

$$v_{ds} = R_s i_{ds} + L_{d0}\frac{di_{ds}}{dt} - L_{q0} i_{qs}\omega_r + \lambda_{qPM}\omega_r \qquad \lambda_{dPM} = \lambda_{dPM.0} + \lambda_{dPM.6}\cos 6\theta_r + \lambda_{dPM.12}\cos 12\theta_r \cdots$$

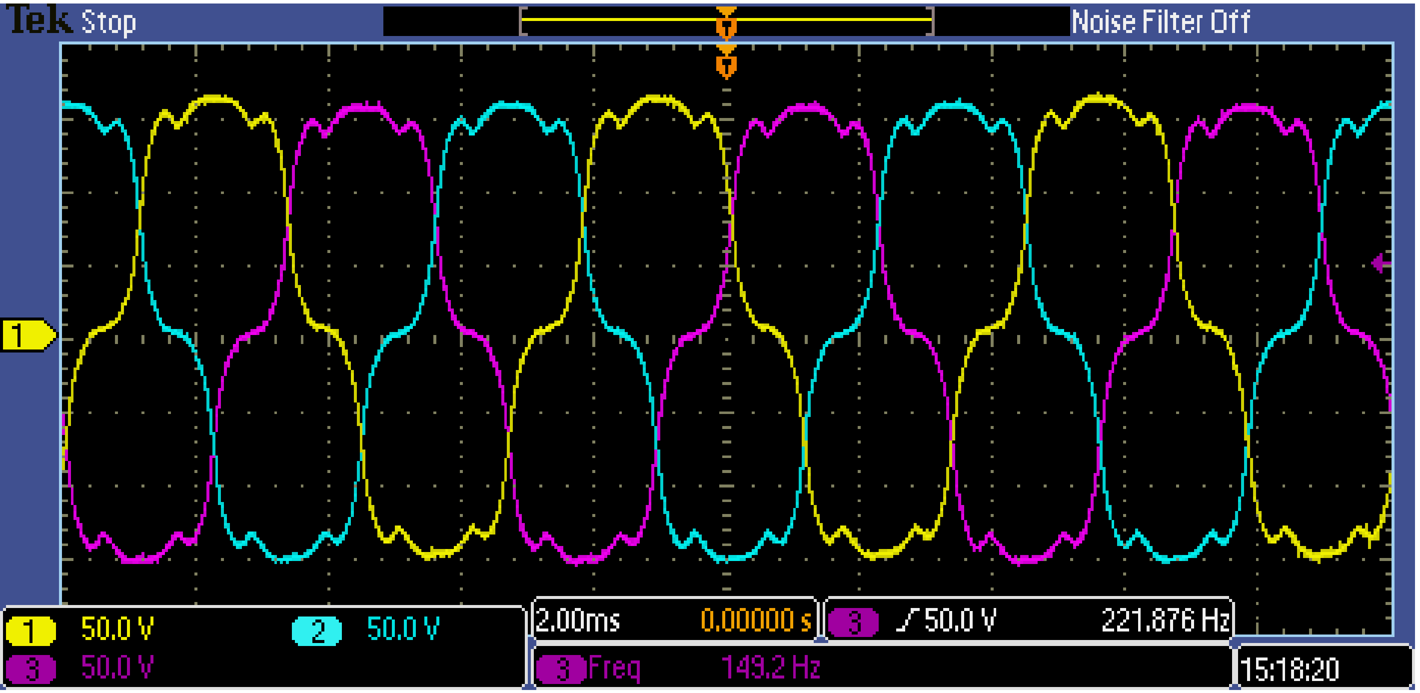
$$v_{qs} = R_s i_{qs} + L_{q0}\frac{di_{qs}}{dt} + L_{d0} i_{ds}\omega_r + \lambda_{dPM}\omega_r \qquad \lambda_{qPM} = \lambda_{qPM.6}\sin 6\theta_r + \lambda_{qPM.12}\sin 12\theta_r \cdots$$

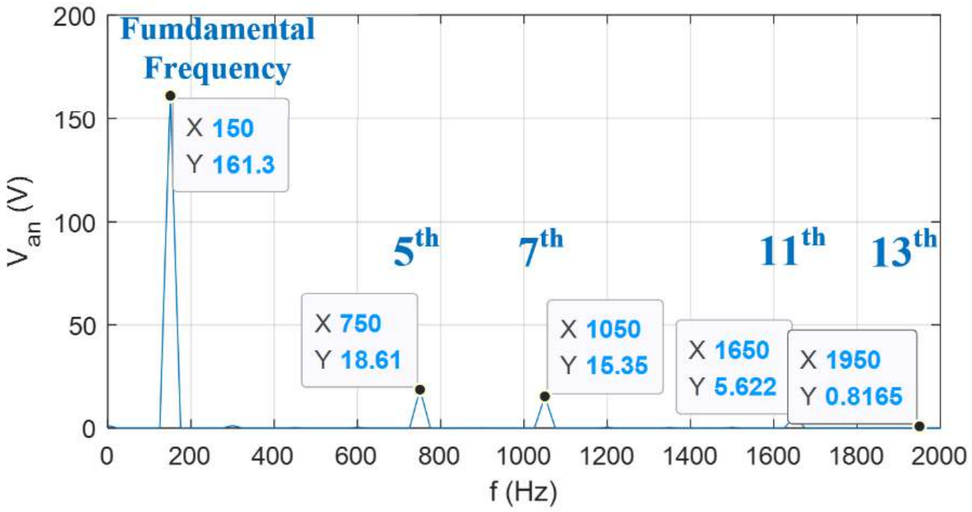
$$T_e = \frac{3}{2}\frac{P}{2}\left[\lambda_{dPM} i_{qs} + \lambda_{qPM} i_{ds} + \left(L_{d0} - L_{q0}\right) i_{qs} i_{ds}\right]$$

- If the motor is manufactured with a high-coercive PM, the effect of the inductance harmonics and mutual inductance is negligible compared to that of rotor magnet flux linkage harmonics [6], [11]
- Assuming $L_d = L_{d0}$ $\quad L_q = L_{q0}$ $\quad L_{dq} = L_{qd} = 0$ $\quad \lambda_{qPM.0} = 0$

Harmonic Identification of Back-EMF

▪ Offline Harmonic Identification





f_{fund}	λ_{fund}	λ_{5th}	λ_{7th}	λ_{11th}	λ_{13th}
$50Hz$	0.1714	0.0197	0.0165	0.0066	0.0008
$100Hz$	0.1711	0.0198	0.0164	0.0063	0.0009
$150Hz$	0.1715	0.0198	0.0163	0.0062	0.0009

$*Unit : Wb-t$

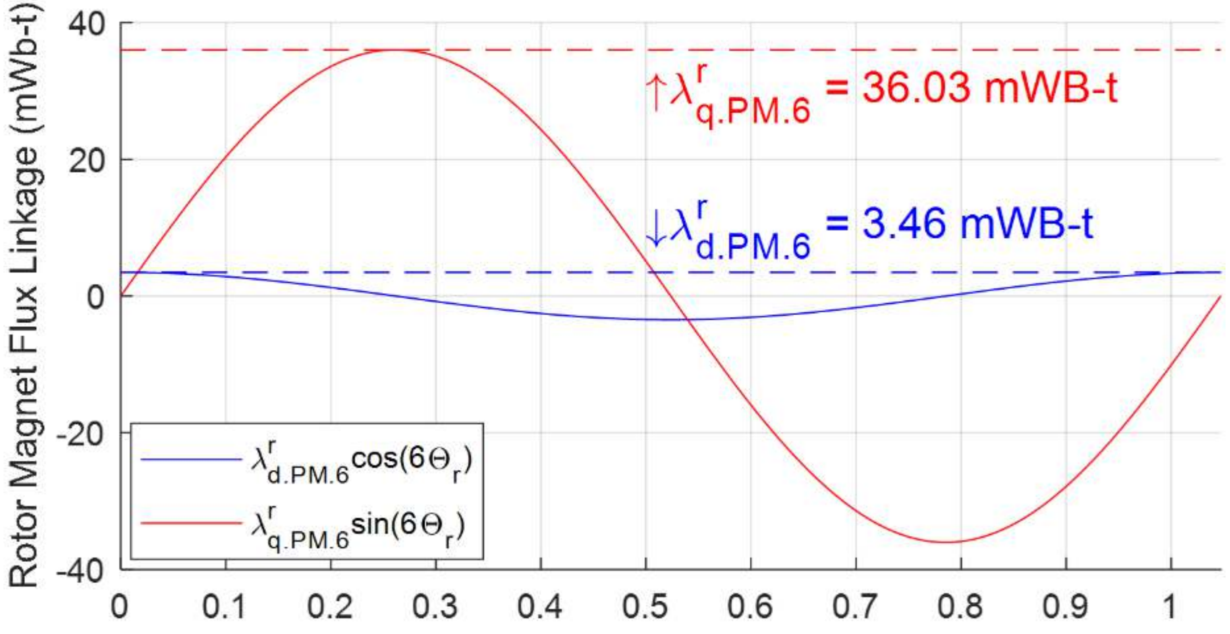
- The saturation effect cannot be considered with offline method
- Online identification is available in [12]

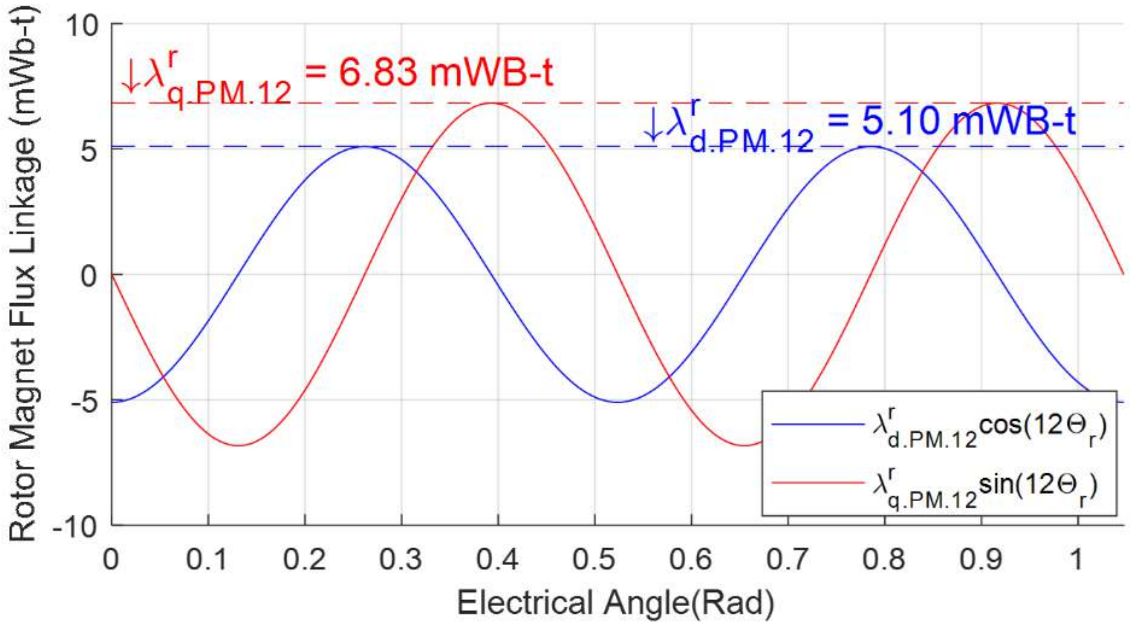
Harmonic Identification of Back-EMF

- **Rotor Magnet Flux Linkage Representation in SRF**

$$v_{ds.emf} = \lambda_{qPM}\omega_r \qquad \lambda_{dPM} = \lambda_{dPM.0} + \lambda_{dPM.6}\cos 6\theta_r + \lambda_{dPM.12}\cos 12\theta_r \cdots$$

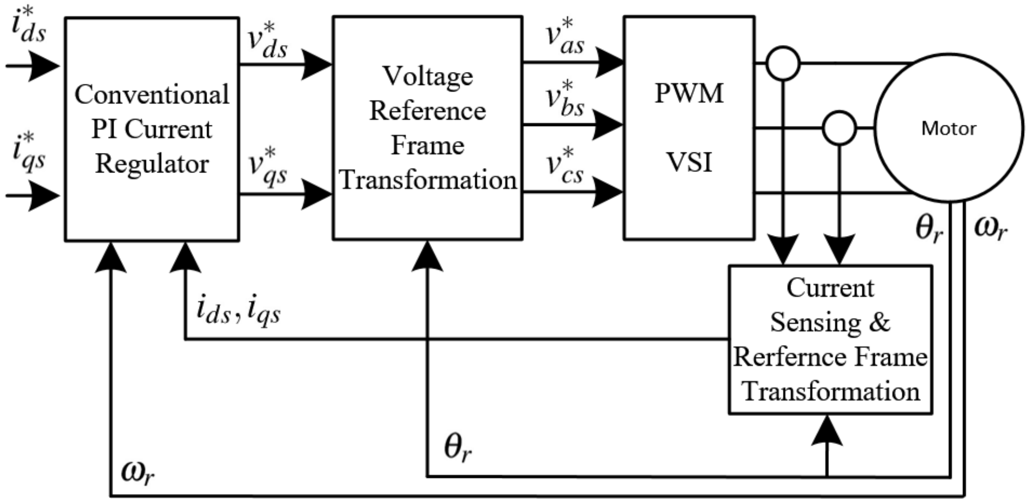
$$v_{qs.emf} = \lambda_{dPM}\omega_r \qquad \lambda_{qPM} = \lambda_{qPM.6}\sin 6\theta_r + \lambda_{qPM.12}\sin 12\theta_r \cdots$$

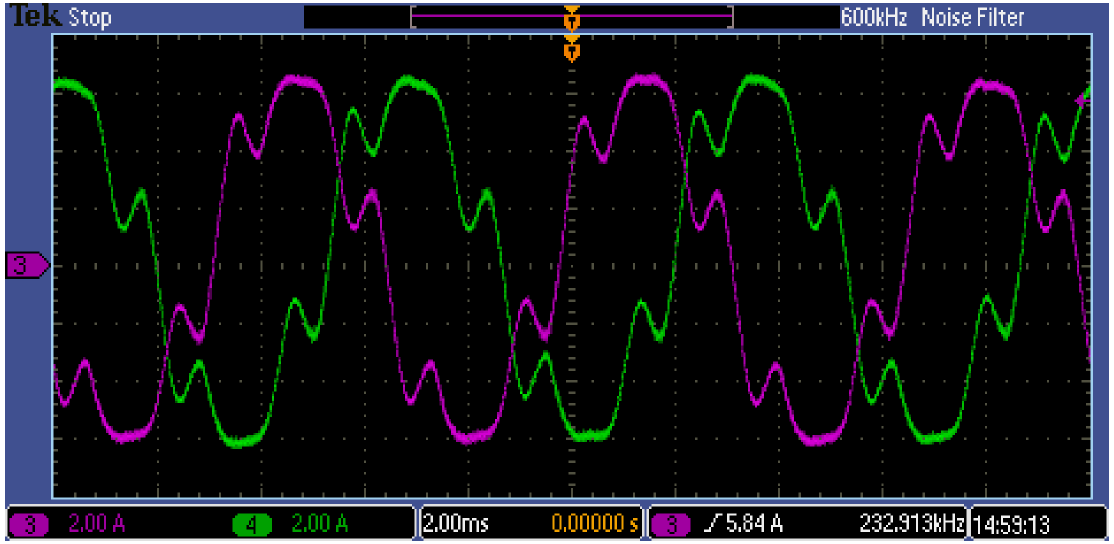




Current Control of PMSMs with Non-sinusoidal Back-EMF

▪ Conventional PI





- Controller mainly serves for the control of fundamental frequency components
- Multiples of 6th harmonic components cannot be handled properly

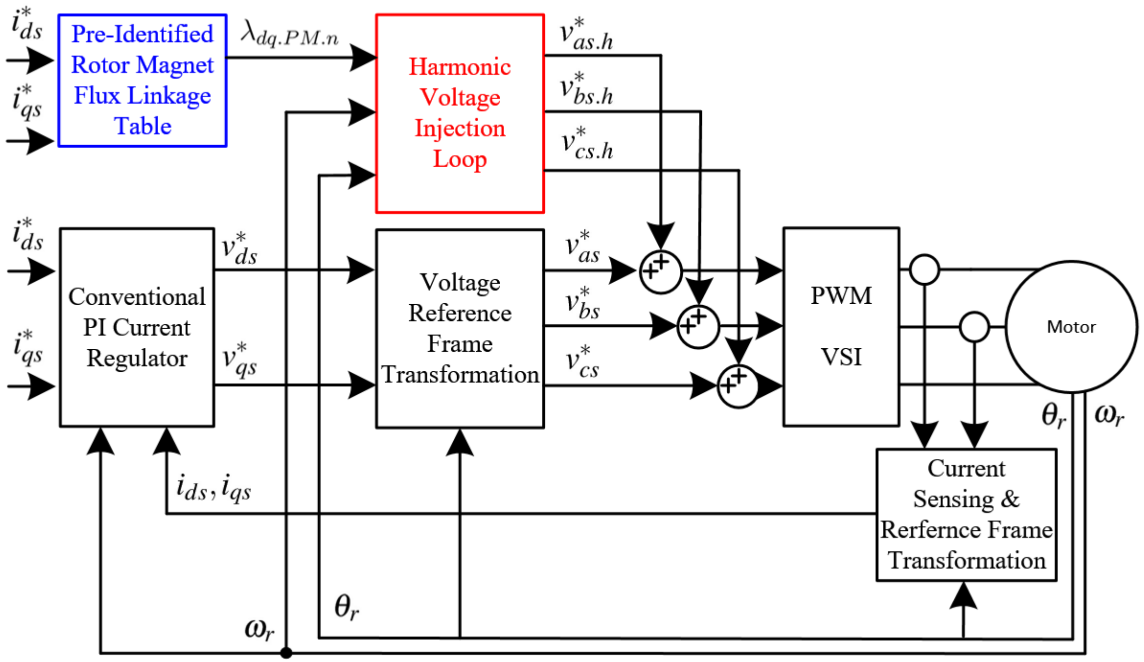
T_{load}	I_{fund}	I_{5th}	I_{7th}	I_{11th}	I_{13th}	THD
25%	1.50A	1.09A	0.90A	0.09A	0.02A	0.94
50%	2.98A	1.10A	0.89A	0.09A	0.02A	0.48
75%	4.49A	1.10A	0.88A	0.10A	0.03A	0.31
100%	6.04A	1.08A	0.87A	0.11A	0.03A	0.23

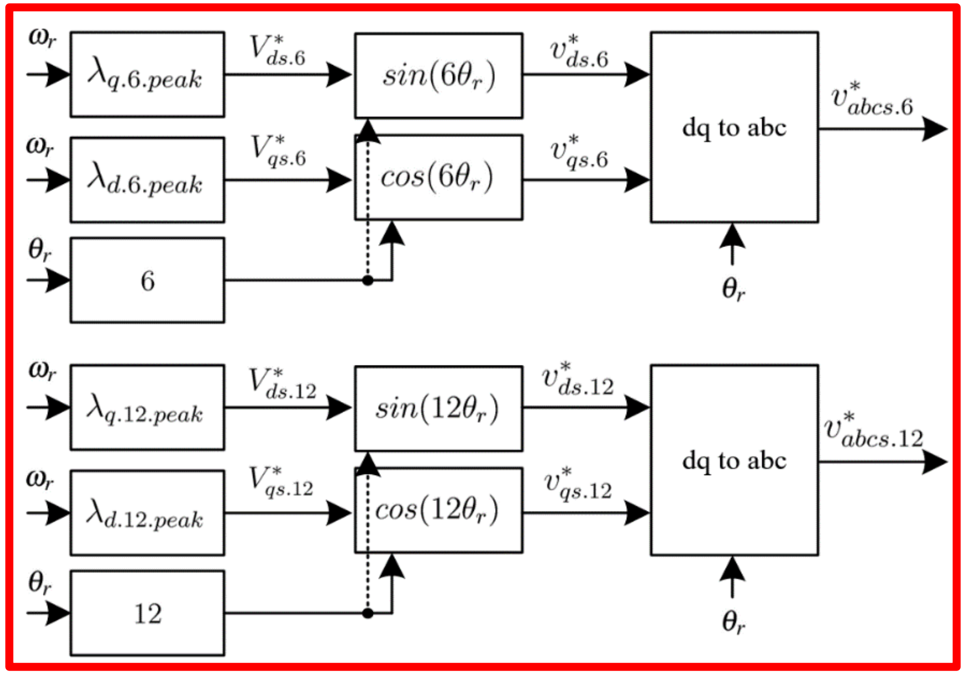
< Tested with various T_e >

Current Control of PMSMs with Non-sinusoidal Back-EMF

▪ Proposed Controller

* PIR controller is available in [12]

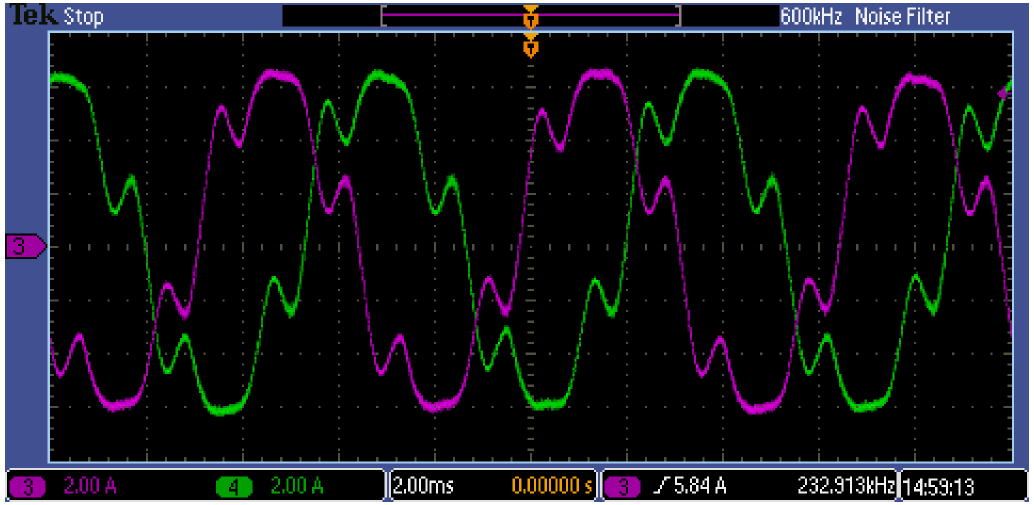




- Harmonic voltage injection loop appears as a feed-forward term
- 6th and 12th harmonic voltages are injected

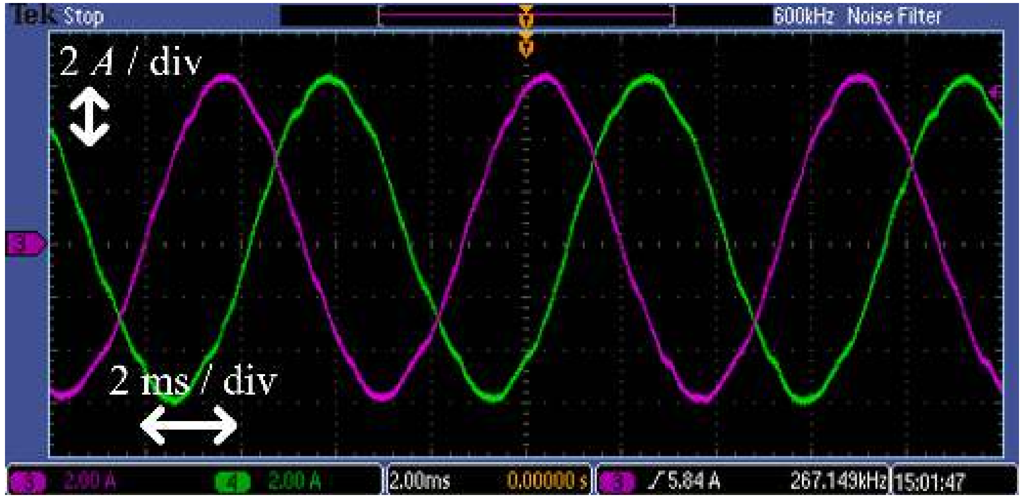
Impact on THD

- **THD Improvement**



T_{load}	I_{fund}	I_{5th}	I_{7th}	I_{11th}	I_{13th}	THD
25%	1.50A	1.09A	0.90A	0.09A	0.02A	0.94
50%	2.98A	1.10A	0.89A	0.09A	0.02A	0.48
75%	4.49A	1.10A	0.88A	0.10A	0.03A	0.31
100%	6.04A	1.08A	0.87A	0.11A	0.03A	0.23

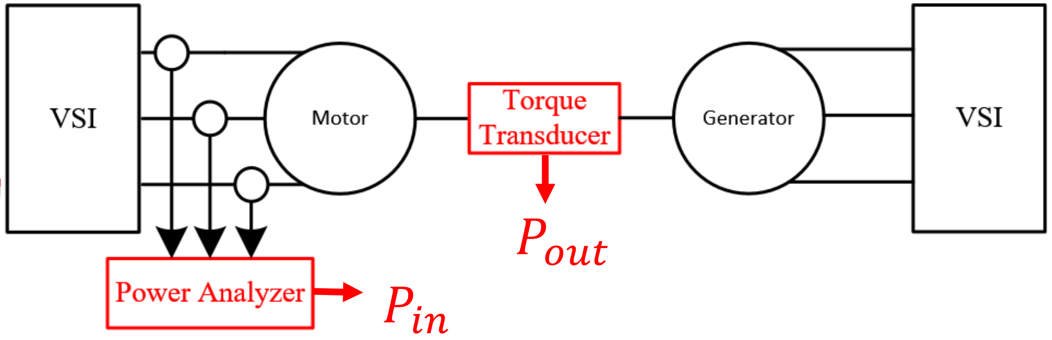
< Conventional PI >



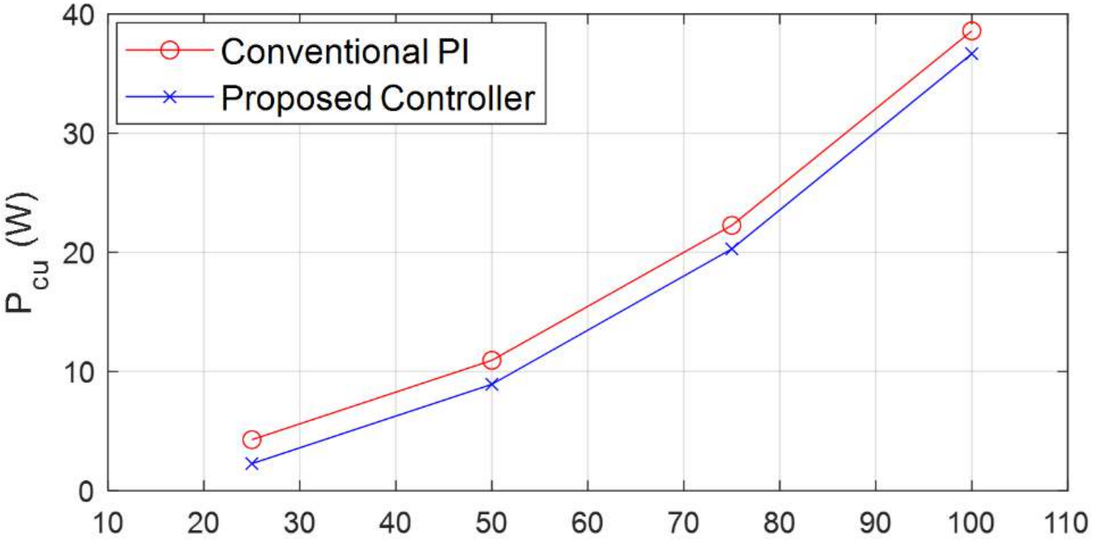
T_{load}	I_{fund}	I_{5th}	I_{7th}	I_{11th}	I_{13th}	THD
25%	1.51A	0.05A	0.06A	0.04A	0.01A	0.06
50%	3.00A	0.10A	0.03A	0.03A	0.02A	0.04
75%	4.48A	0.09A	0.05A	0.08A	0.02A	0.03
100%	5.98A	0.08A	0.05A	0.07A	0.02A	0.02

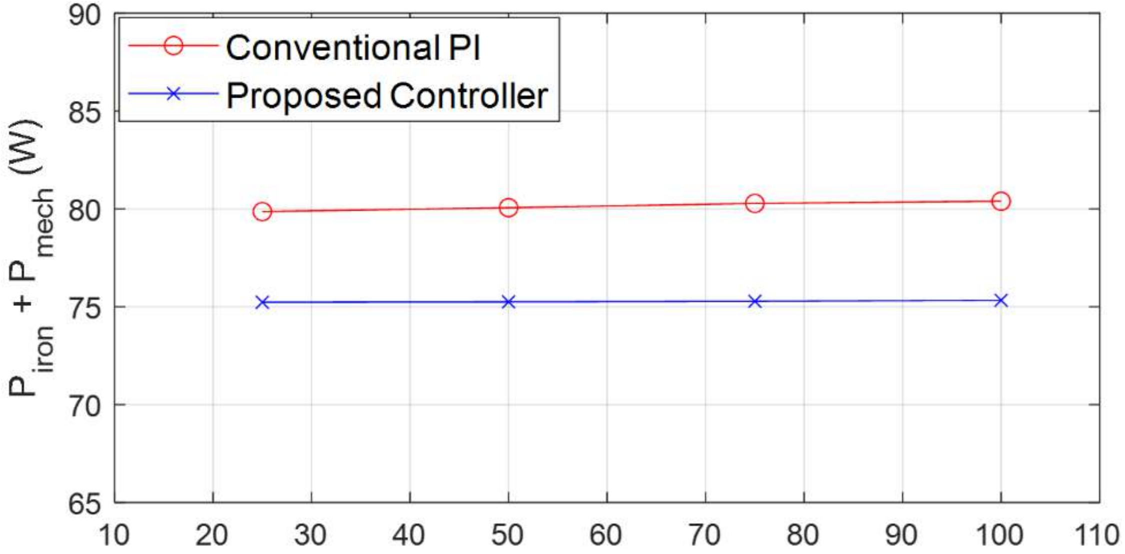
< Proposed Control >

Impact on Power Loss



- **Power Loss Improvement**





T_L	25%	50%	75%	100%
ΔP_{cu}	2.02W	2.02W	2.01W	1.95W
ΔP_{iron}	4.63W	4.81W	5.00W	5.06W
ΔP_{total}	6.65W	6.83W	7.01W	7.01W
$\Delta\eta$	1.77%	0.91%	0.62%	0.47%

$$\Delta P_{total} = \Delta P_{cu} + \Delta P_{iron}$$

$$P_{cu} = R_s(I_{Arms}^2 + I_{Brms}^2 + I_{Crms}^2)$$

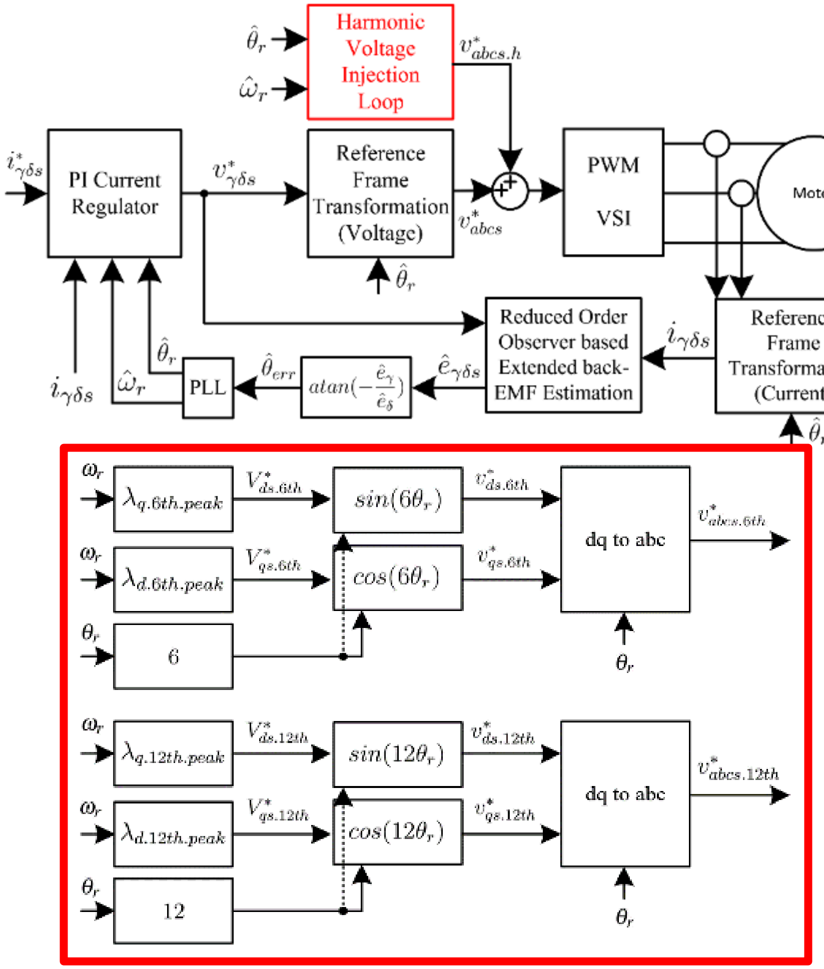
$$P_{iron} + P_{mech} = P_{in} - P_{out} - P_{cu}$$

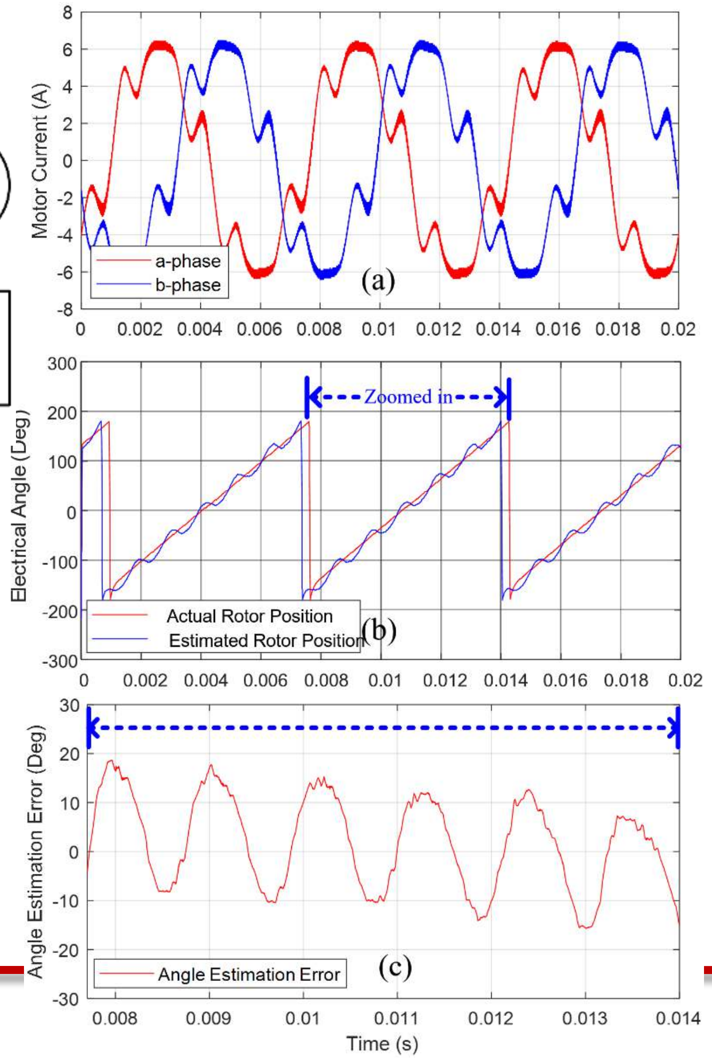
$$\Delta\eta = \frac{\Delta P_{total}}{P_{in}}$$

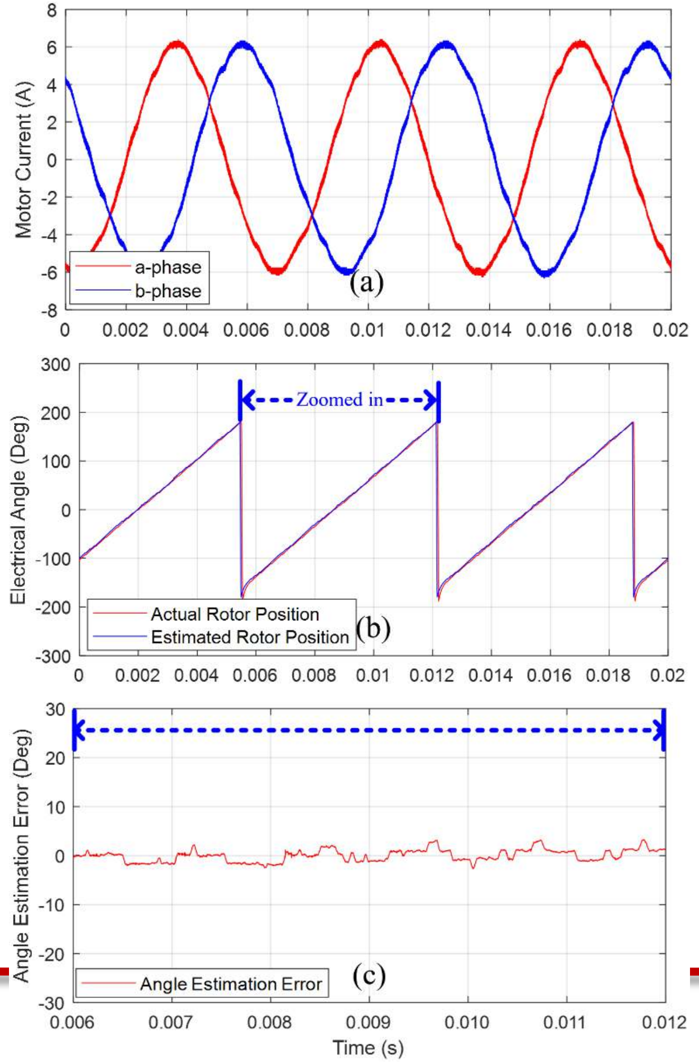
Impact on EEMF-Based Sensorless Control

- **Angle Estimation Improvement [13]**

Proposed ↓







Conventional →

Ongoing Research

- Injecting optimal 6^{th} and 12^{th} harmonic currents to reduce torque ripple in low-speed range [10]
- Current control for minimizing cross-coupling effect [14]
- Sensorless control for low-speed range
- Experimental harmonic identification of self- and cross-coupling inductance

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Q & A