27th International Conference on Electrical Machines
Funchal, Madeira, Portugal | September 6-9, 2026

Paper Number ICEM26-000408

Torque Ripple Suppression in Synchronous Machine Drives by Frequency-Adaptive PIR Current Control

Niklas Monzen, Pascal Seitter, and Christoph M. Hackl

Laboratory for Mechatronic and Renewable Energy Systems (LMRES), Hochschule München (HM) University of Applied Sciences, Munich, Germany | christoph.hackl@hm.edu

Abstract

Torque ripple in permanent magnet synchronous machine (PMSM) drives causes vibrations, acoustic noise and degraded control performance. This paper proposes a **generic torque ripple suppression (TRS)** strategy: the loss-optimal current reference of an optimal feedforward torque control (OFTC) is superimposed by an **angle-dependent q-current correction** $i^q_{\mathrm{s,trs}}(\phi_\mathrm{m})$. The resulting multi-harmonic reference is tracked by a **parallelized PIR$_\mathbb{H}$ current controller** tuned by **frequency-adaptive pole placement (FAPP)**.

Novelties of this paper

- **TRS:** angle-dependent current shaping $i^q_{\mathrm{s,trs}}(\phi_\mathrm{m})$ from a *generalized* current/speed/angle-dependent torque model
- **PIR$_\mathbb{H}$ + FAPP:** parallelized resonant current control, analytically tuned and speed-adaptive for any harmonic set $\mathbb{H}$

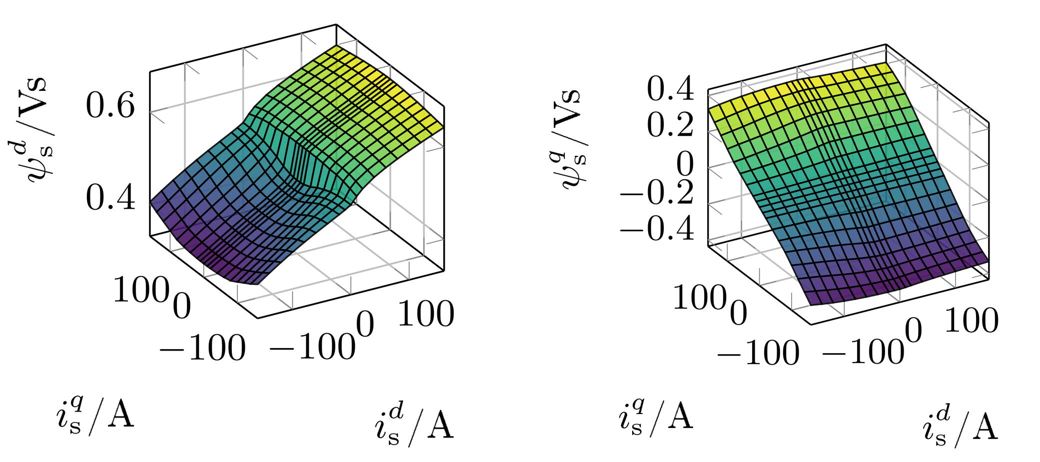
Problem and proposed TRS framework

Nonlinear machine model

Stator current dynamics in the rotor-oriented (d,q)-reference frame:

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}^{dq}_\mathrm{s} = (\boldsymbol{L}^{dq}_\mathrm{s})^{-1}\big(\boldsymbol{u}^{dq}_\mathrm{s} - \boldsymbol{R}^{dq}_\mathrm{s}\boldsymbol{i}^{dq}_\mathrm{s} - \omega_\mathrm{p}\boldsymbol{J}\boldsymbol{\psi}^{dq}_\mathrm{s} - \boldsymbol{\delta}^{dq}_\mathrm{s}\big), \qquad \boldsymbol{\delta}^{dq}_\mathrm{s} = \tfrac{\partial\boldsymbol{\psi}^{dq}_\mathrm{s}}{\partial\phi_\mathrm{m}}\omega_\mathrm{m} + \tfrac{\partial\boldsymbol{\psi}^{dq}_\mathrm{s}}{\partial\omega_\mathrm{m}}\tfrac{\mathrm{d}}{\mathrm{d}t}\omega_\mathrm{m}$$

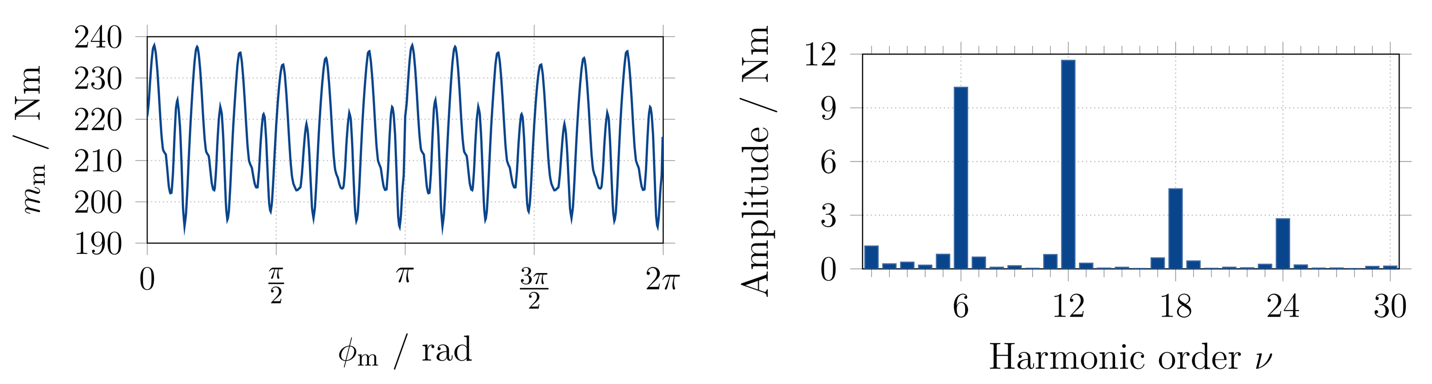
Flux linkages $\boldsymbol{\psi}^{dq}_\mathrm{s}$, differential inductances $\boldsymbol{L}^{dq}_\mathrm{s}$, torque m_m and the induced voltage $\boldsymbol{\delta}^{dq}_\mathrm{s}$ are **current-, speed- and angle-dependent** and stored as 4D-LUTs over $(i^d_\mathrm{s}, i^q_\mathrm{s}, \omega_\mathrm{m}, \phi_\mathrm{m})$ obtained from FEA.



Flux linkages ψ^d_s (left) and ψ^q_s (right): saturation and cross-coupling.

Angle-dependent torque and its ripple

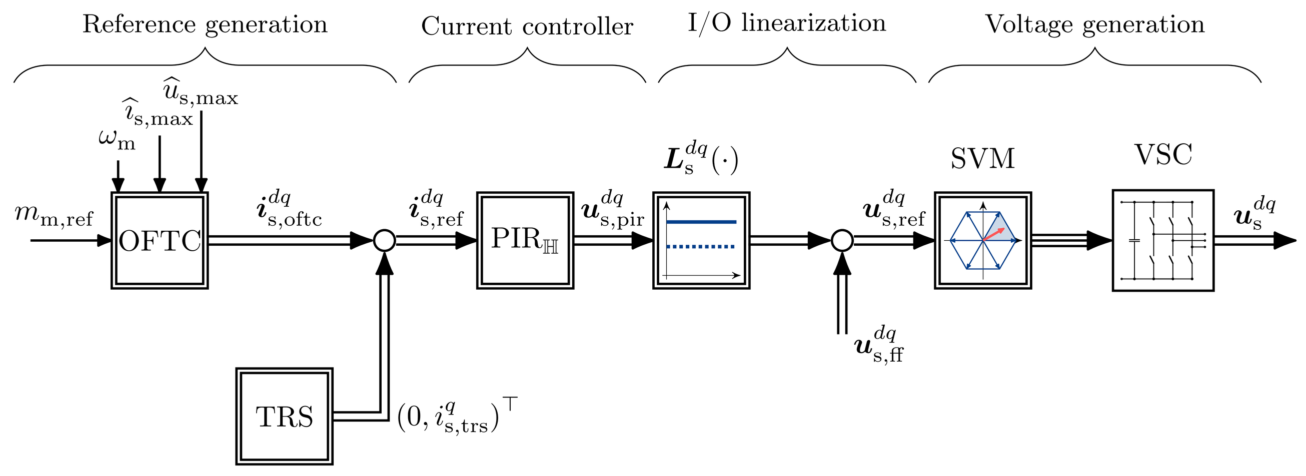
At the nominal operating point ($m_\mathrm{m,R} = 215\,$Nm, $\omega_\mathrm{m,R} = 377\,\frac{\mathrm{rad}}{\mathrm{s}}$) the torque oscillates over the rotor angle with a **peak-to-peak ripple of** $\approx 44\,$Nm $\approx 20\,\%$ **of** $m_\mathrm{m,R}$:



Machine torque $m_\mathrm{m}(\phi_\mathrm{m})$ (left) and its FFT harmonic spectrum (right).

Dominant orders $\nu \in \{6, 12, 18, 24\}$ $\Rightarrow$ harmonic set $\mathbb{H} = \{0, \pm 6, \pm 12, \pm 18, \pm 24\}$. OFTC alone *cannot* suppress the ripple, a PI controller *cannot* track multi-harmonic references.

Proposed TRS framework



OFTC + TRS, PIR$_\mathbb{H}$ controller with FAPP, I/O linearization, SVM and VSC.

Control system and validation

Reference currents: OFTC + TRS

Loss-optimal OFTC **[1]** plus the proposed angle-dependent TRS correction:

$$\boldsymbol{i}^{dq}_\mathrm{s,ref} = \boldsymbol{i}^{dq}_\mathrm{s,oftc} + (0,\ i^q_\mathrm{s,trs})^\top,$$

$$\boldsymbol{i}^{dq}_\mathrm{s,oftc} = \arg\min_{\boldsymbol{i}^{dq}_\mathrm{s}} p_\mathrm{L}(\boldsymbol{i}^{dq}_\mathrm{s}, \omega_\mathrm{m}, \phi_\mathrm{m}) \quad \text{s.t.} \quad m_\mathrm{m} = m_\mathrm{m,ref}, \quad \|\boldsymbol{i}^{dq}_\mathrm{s}\| \le \hat{\imath}_\mathrm{s,max}, \quad \|\boldsymbol{u}^{dq}_\mathrm{s}\| \le \hat{u}_\mathrm{s,max}$$

TRS current shaping – for every operating point *and* every rotor angle, from the generalized torque map:

$$i^q_\mathrm{s,trs} := \arg\min_{\Delta i^q_\mathrm{s}} \big(m_\mathrm{m,ref} - m_\mathrm{m}(i^d_\mathrm{s,oftc},\ i^q_\mathrm{s,oftc} + \Delta i^q_\mathrm{s},\ \omega_\mathrm{m},\ \phi_\mathrm{m})\big)^2$$

Current control: PIR$_\mathbb{H}$ with FAPP

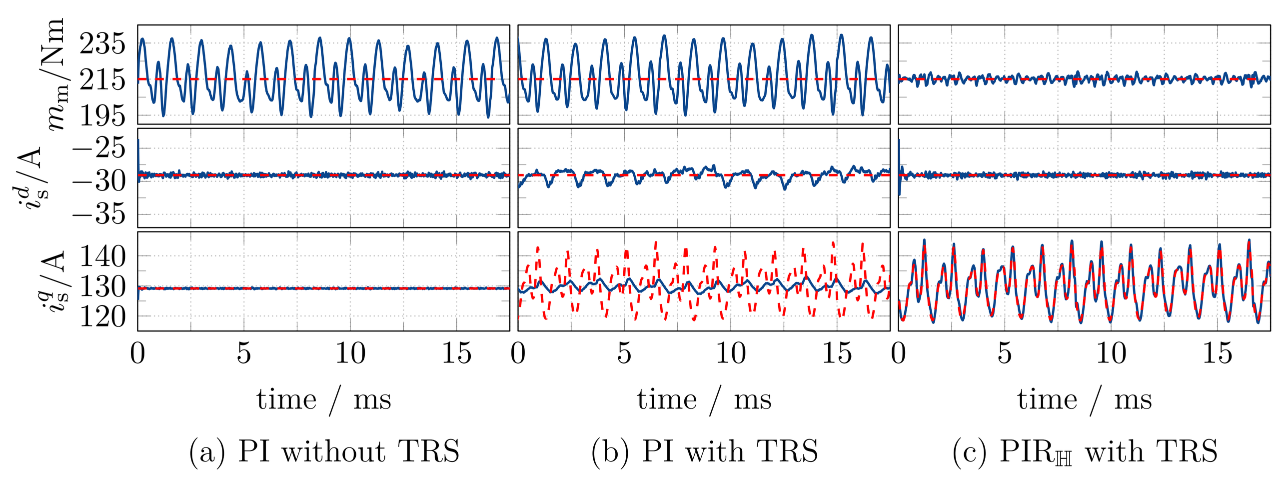
I/O linearization **[3]**, $\boldsymbol{u}^{dq}_\mathrm{s,ref} := \boldsymbol{L}^{dq}_\mathrm{s}\boldsymbol{u}^{dq}_\mathrm{s,pir} + \boldsymbol{u}^{dq}_\mathrm{s,ff}$, turns the current dynamics into integrators, $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}^{dq}_\mathrm{s} = \boldsymbol{u}^{dq}_\mathrm{s,pir}$:

$$\boldsymbol{u}^{dq}_\mathrm{s,pir} = \omega_0\Big[\boldsymbol{K}_\mathrm{p}\boldsymbol{e} + \boldsymbol{K}_\mathrm{i}\boldsymbol{x}_\mathrm{i} + \sum_{\nu\in\mathbb{H}}\boldsymbol{K}_\nu\boldsymbol{x}_\nu\Big], \qquad \omega_0(t) = \alpha_\mathrm{m} n_\mathrm{p}\omega_\mathrm{m,R}\Big(\beta_\mathrm{m} + \tfrac{|\omega_\mathrm{m}(t)|}{\omega_\mathrm{m,R}}\Big)$$

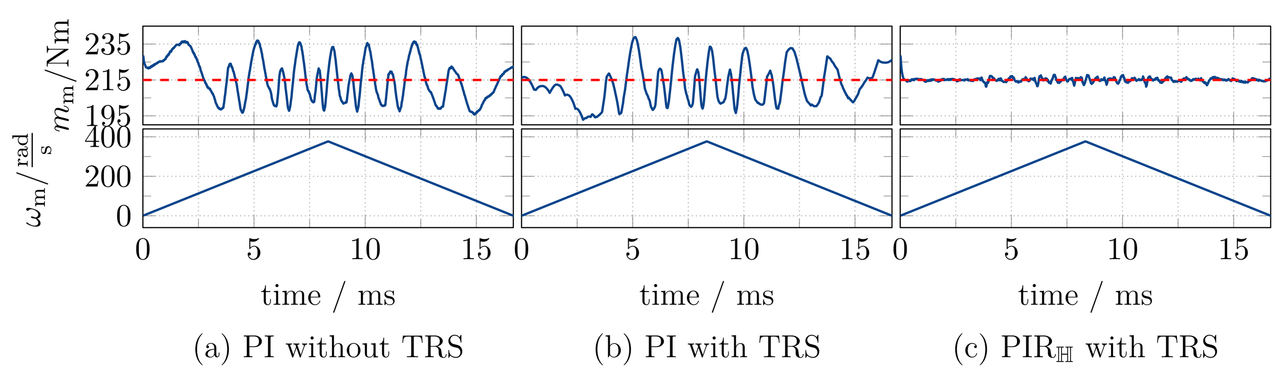
One resonator per $\nu \in \mathbb{H}$ (20 states), **all gains placed analytically by FAPP [2]** and **scaled with the actual speed** $\Rightarrow$ consistent dynamics over the whole speed range.

Validation

Nonlinear FEA-based IPMSM ($81\,$kW, $215\,$Nm, $377\,\frac{\mathrm{rad}}{\mathrm{s}}$) with switching VSI ($f_\mathrm{sw} = 64\,$kHz, SVM); references [- -], actual values [—].



Scenario 1: constant speed $\omega_\mathrm{m} = \omega_\mathrm{m,R}$.



Scenario 2: speed ramp $0 \to \omega_\mathrm{m,R} \to 0$ within $20\,$ms.

(a) $\approx 20\,\%$ peak-to-peak ripple – (b) no improvement – (c) $\approx 4\,\%$: **fivefold reduction** in both scenarios.

Conclusion & References

- Generic TRS: OFTC currents + angle-dependent q-current shaping, tracked by a parallelized PIR$_\mathbb{H}$ controller with FAPP.
- Peak-to-peak torque ripple reduced from $\approx 20\,\%$ to $\approx 4\,\%$ of $m_\mathrm{m,R}$ – also under extreme speed ramps.
- Next: experiments, robustness analysis, extension to EESMs.

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[2] C. Göttsberger, C. M. Hackl, “Frequency-adaptive pole placement for parallelized proportional, integral and resonant control systems,” *IECON*, 2025.

[3] S.-W. Su, H. Börngen, C. M. Hackl, R. Kennel, “Nonlinear current control of reluctance synchronous machines,” *IEEE OJ-IES*, 2022.