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Constrained Optimization-Based Neuro-Adaptive Control (CONAC) for Synchronous Machine Drives Under Voltage Constraints (ID: 1360)

Myeongseok Ryu*, Niklas Monzen**, Pascal Seitter**, Kyunghwan Choi* and Christoph M. Hackl**

(*) CCS Graduate School of Mobility, KAIST, Republic of Korea and (**) LMRES, Hochschule Műnchen, Germany

KAIST HM

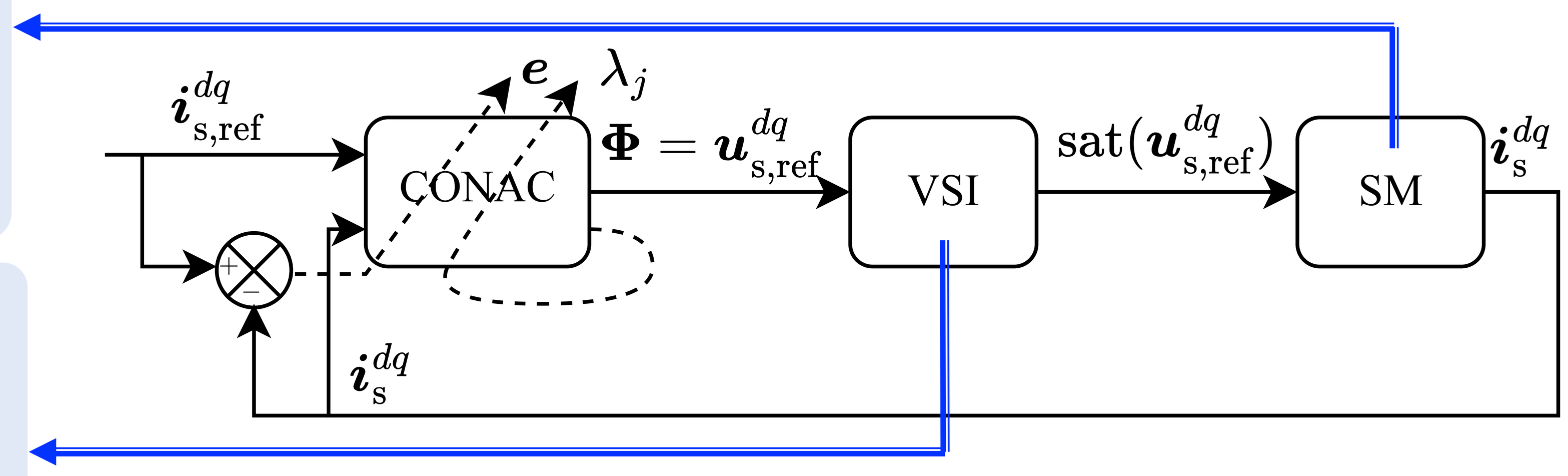
Background

Motivation 1:

Exact system knowledge is required, e.g., resistances and flux linkages

Motivation 2:

Input saturation by voltage source inverter (VSI)



Nomenclature

- $\widehat{\theta}_i$: estimated weight of ith layer
- θ_i^*: ideal weight of ith layer
- x_n: artifical neural network (ANN) input
- $\Phi(x_n;\theta)$: ANN function
- α: learning rate of weights
- β: update rate of Lagrange multipliers

Proposed Method (CONAC)

SM drive modeling

Resistances Flux linkages

$$\mathrm{sat}(u_{s,ref}^{dq}) = R_s^{dq} i_s^{dq} + \omega_p J \psi_s^{dq} + \frac{d}{dt}\psi_s^{dq}$$

Saturation (VSI) Control input (voltage) State (current) Unknown terms

Controller design objectives

- Design current tracking controller
- Utilize ANN to approximate unknown ideal input *(Motivation 1)*

$$u^* = \Phi(x_n;\theta^*) + \epsilon, \text{ and } u_{s,ref}^{dq} = \widehat{\Phi} = \Phi(x_n;\widehat{\theta})$$

Ideal unknown control input Actual input (ANN output)

- Derive ANN weight adaptation law ensuring stability (weight and error boundedness) and preventing input saturation *(Motivation 2)*

$$\frac{d}{dt}\widehat{\theta} = ?, \text{ which leads } \widehat{\theta} \to \theta^*$$

Constraints formulation

- Constraint 1: Weight boundedness (1 hidden layer)

$$c_{\theta_i}(\widehat{\theta}) = \frac{1}{2}(\widehat{\theta}_i^\top \widehat{\theta}_i - \bar{\theta}_i^2) \le 0, \quad \forall i \in \{0,1\} \quad (1)$$

- Constraint 2: Input saturation

$$c_u(\widehat{\theta}) = \frac{1}{2}(\widehat{\Phi}^\top \widehat{\Phi} - \bar{u}^2) \le 0 \quad (2)$$

Constrained optimization problem

- Quadratic objective function $J(\cdot)$ of tracking error $e := i_s - i_{s,ref}$

$$\min_{\widehat{\theta}} J(e;\widehat{\theta}) = \frac{1}{2} e^\top e,$$

$$\text{subject to } (1) \text{ and } (2)$$

- Lagrangian function

λ_j: Lagrange multipliers

$\mathcal{I}$: Inequality constraint set

$$L(e,\widehat{\theta},[\lambda_j]_{j\in\mathcal{I}}) := J(e;\widehat{\theta}) + \sum_{j\in\mathcal{I}} \lambda_j c_j(\widehat{\theta})$$

Adaptation law derivation

$$\min_{\widehat{\theta}} \max_{[\lambda_j]_{j\in\mathcal{I}}} L(e,\widehat{\theta},[\lambda_j]_{j\in\mathcal{I}})$$

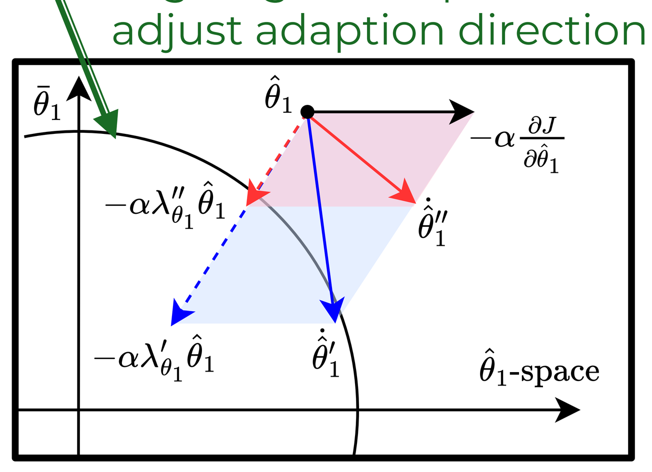
- Gradient descent/ascent methods (dual problem)

$$\frac{d}{dt}\widehat{\theta} = -\alpha\frac{\partial L}{\partial \widehat{\theta}} = -\alpha\left(\frac{\partial J}{\partial \widehat{\theta}} + \sum_{j\in\mathcal{I}} \lambda_j \frac{\partial c_j}{\partial \widehat{\theta}}\right), \quad (3)$$

$$\frac{d}{dt}\lambda_j = \beta_j \frac{\partial L}{\partial \lambda_j} = \beta_j c_j, \quad \forall j \in \mathcal{I},$$

$$\lambda_j \leftarrow \max(\lambda_j, 0)$$

Lagrange multipliers adjust adaption direction



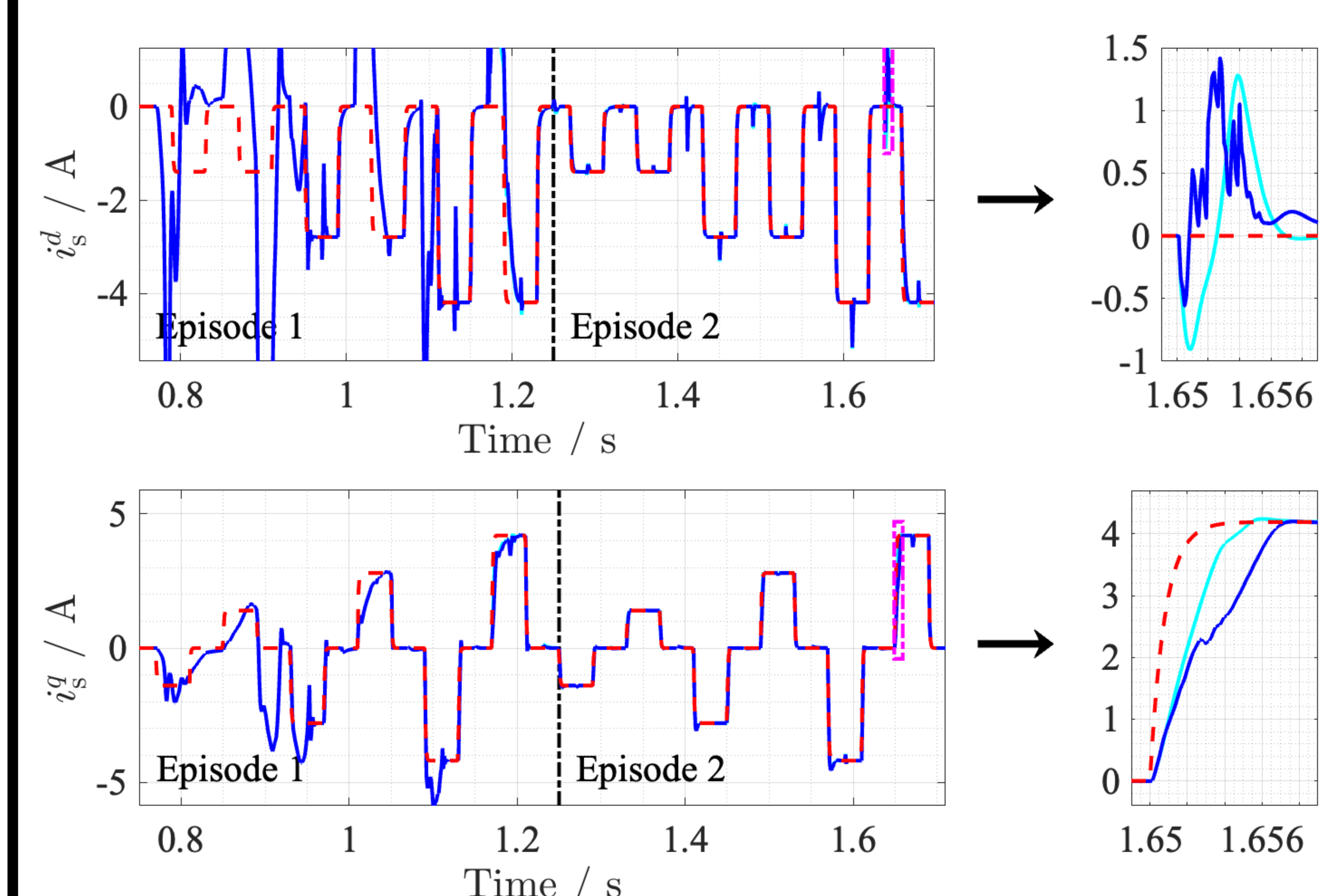
Contributions

- No prior system information is required
- Adaptation laws are derived based on constrained optimization
- Stability is guaranteed using Lyapunov theory, see Thm. 1 in Paper

$$\|e\| \le \frac{\bar{u}}{k}, \text{ and } \|\widehat{\theta}_i\| \le \bar{\theta}_i, \ \forall i \in \{0,1\}$$

Numerical Validation

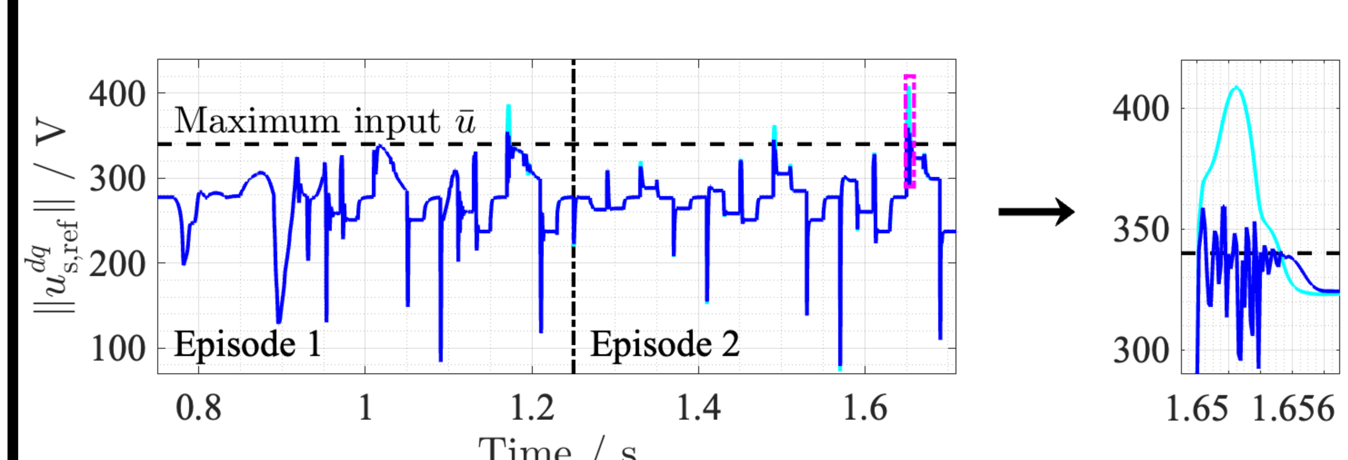
- (C1) CONAC with input constraint
- (C2) CONAC without input constraint
- Reference current



Tracking Performance

- Both controllers demonstrated satisfactory performance
- Performance was improved in Episode 2, ≅ -84%
- (C2) achieved slightly higher performance
  - However, it neglected costs that come from saturation

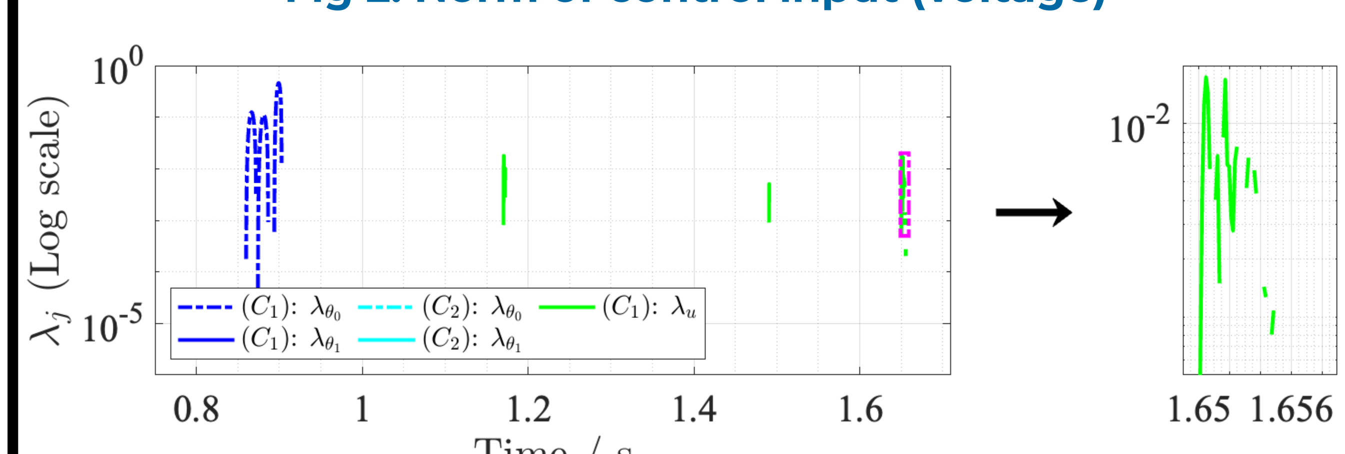
Fig 1. Current tracking results



Input Saturation

- Input saturation of (C1) was suppressed
- (C2) exceeded the input limit, ≅ +85%

Fig 2. Norm of control input (voltage)



Constraint Handling

- Lagrange multipliers increase to adjust adaptation, see eq. (3)

Fig 3. Lagrange multipliers in logarithmic scale

Table 1. Quantitative comparison of performances' L_2 norm

	Episode 1			Episode 2		
	(C1)	(C2)	%	(C1)	(C2)	%
$i_s^d - i_{s,ref}^d$	1.835	1.835	+0.0	0.119	0.117	+1.3
$i_s^q - i_{s,ref}^q$	0.597	0.591	+1.0	0.157	0.126	+19.6
$\max(c_u, 0)$	0.297	2.031	−85.9	0.488	3.251	−85.0

Conclusion

- CONAC was proposed for SM drives with input voltage saturation
- Stability and constraint satisfaction were ensured via Lyapuonv theory
- As future work, the following subjects will be investigated
  - The parameter dependencies of CONAC
  - Real-time implementation to validate the effectiveness and feasibility

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