Neural Network-Based Imitation of Model Predictive Control for Power Converters

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Introduction

- Finite-set model predictive control (FS-MPC) is an advanced control algorithm that offers very accurate steady-state and transient performance at the cost of high computational requirements [1].
- Artificial neural networks (ANNs) are a type of machine-learning model that can approximate any arbitrarily complex function and be evaluated in a computationally efficient manner [2].
- By training ANN imitators of FS-MPC, the computational drawbacks of FS-MPC can be greatly reduced while maintaining the performance of the algorithm.

Analysis

- The FS-MPC algorithm is based on the state-space model of an LC filter:

$$\dot{\mathbf{x}}(t) = \mathbf{A} \cdot \mathbf{x}(t) + \mathbf{B} \cdot \mathbf{u}(t) \tag{1}$$

$$\mathbf{x}(t) = \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} \quad \mathbf{u}(t) = \begin{bmatrix} v_i(t) \\ i_{load}(t) \end{bmatrix} \tag{2}$$

- The coefficient matrices of the state-space model are:

$$\mathbf{A} = \begin{bmatrix} -\frac{R_f}{L_f} & -\frac{1}{L_f} \\ \frac{1}{C_f} & 0 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & -\frac{1}{C_f} \end{bmatrix} \tag{3}$$

- This model is discretized and implemented in an FS-MPC algorithm, which solves in real time the optimization problem corresponding to minimizing the error between predicted output and reference voltages.

Conclusion

- The obtained ANN-based imitators closely match the behavior of FS-MPC.
- The imitators are shown to be robust to changes in reference voltage.
- This study shows that a 3-step FS-MPC algorithm with an unfeasible real-time implementation may be successfully imitated by a feasible ANN-based controller trained using adequate data.

References

[1] Samir Kouro et al. "Model predictive control - A simple and powerful Method to control power converters". In: *IEEE Transactions on Industrial Electronics* 56.6 (2009), pp. 1826–1838. ISSN: 02780046. DOI: 10.1109/TIE.2008.2008349.

[2] Kurt Hornik, Maxwell Stinchcombe, and Halbert White. "Multilayer feedforward networks are universal approximators". In: *Neural Networks* 2.5 (1989), pp. 359–366. ISSN: 08936080. DOI: 10.1016/0893-6080(89)90020-8.

Artificial neural network training

- The artificial neural network imitators are trained using two million data points obtained from offline simulations of FS-MPC.
- The training is performed using the *Python 3* implementation of the *TensorFlow* library and making extensive use of the *Keras* API.
- Figure 1 illustrates the basic structure of an ANN.
- Figure 2 shows how the error and total harmonic distortion (THD) are reduced when the number of neurons of the network increases. Based on it, a 15-neuron architecture was selected.

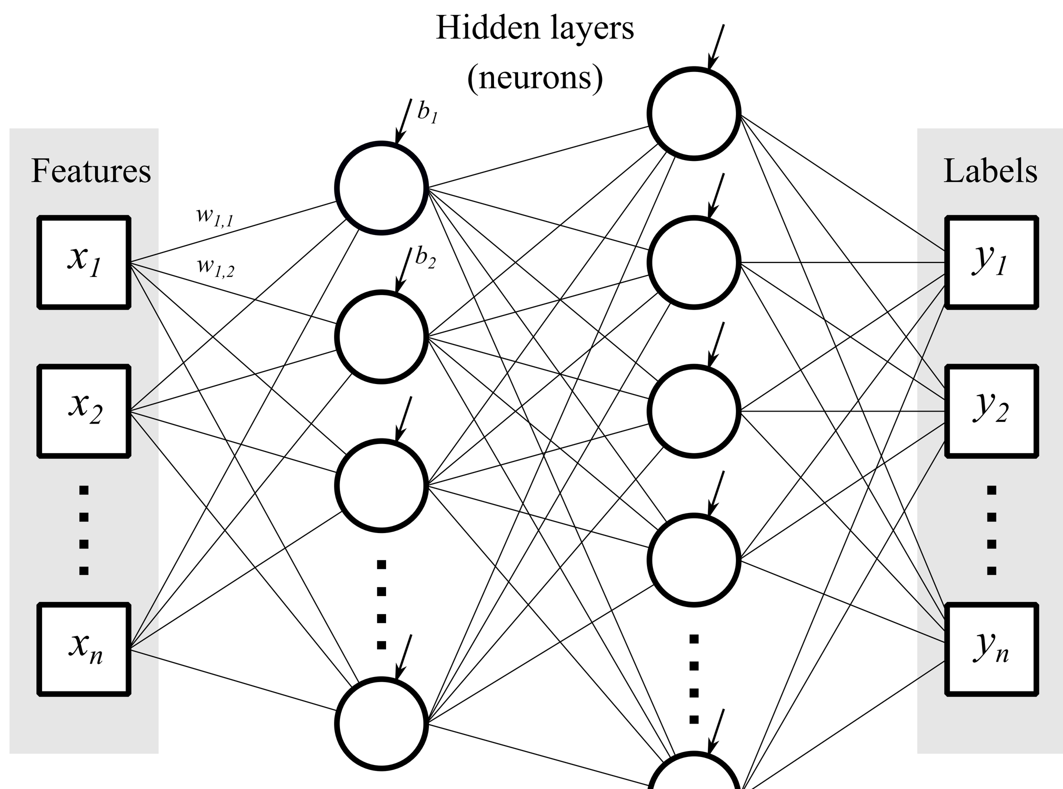

Fig. 1: General diagram neural network.

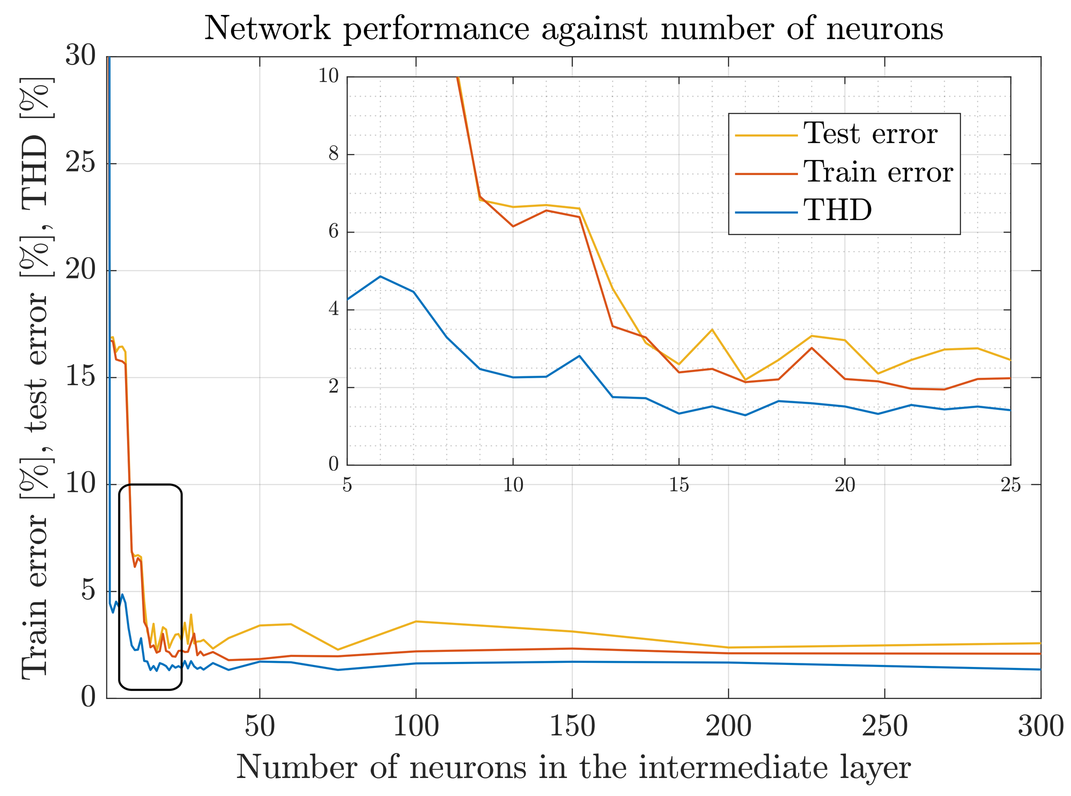

Fig. 2: Train error, test error, and THD against number of neurons in the intermediate layer.

Experimental Results

- When looking at Figures 3 and 4 one may wonder why the same image is shown twice. This highlights the effectiveness of the imitation method as the difference in performance are barely noticeable.

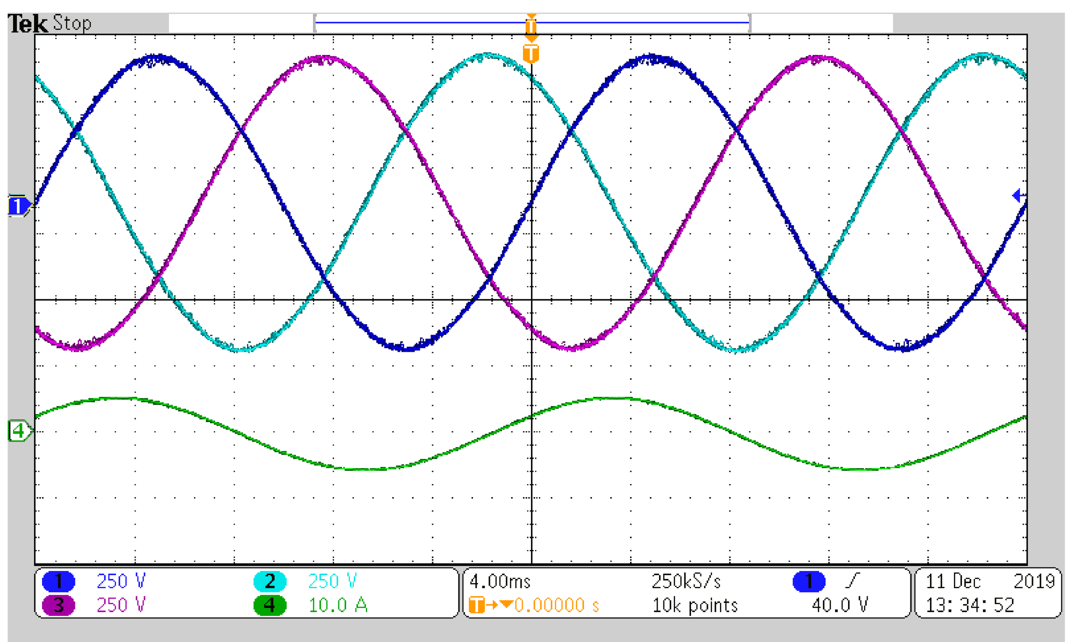

Fig. 3: FS-MPC for 1 step prediction steady-state performance with a 325 V reference amplitude and R_{load} = 60 Ω. THD = 1.654%

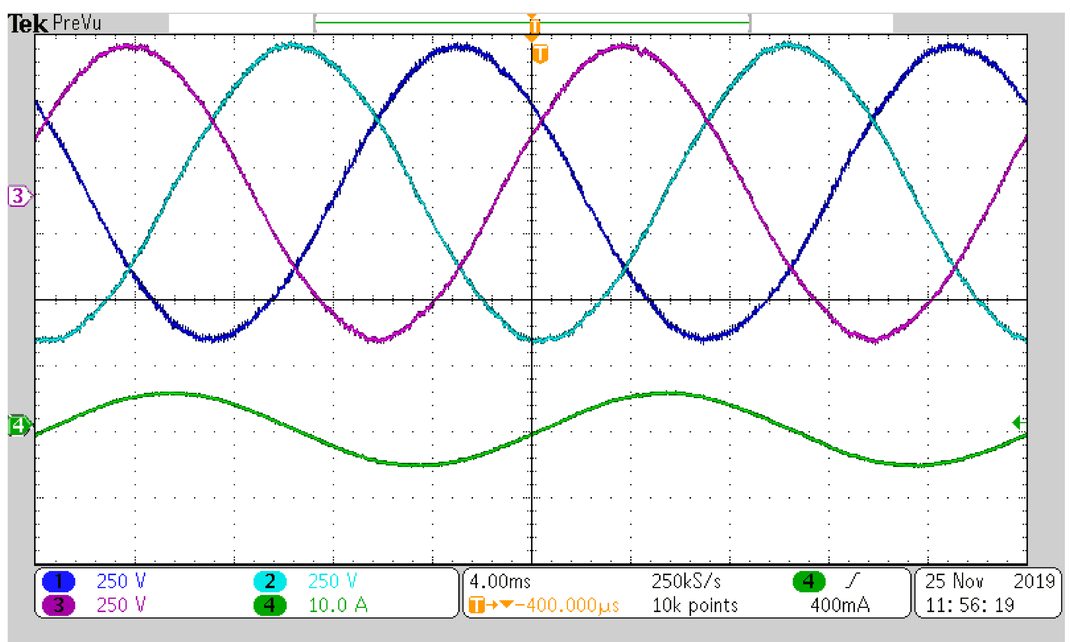

Fig. 4: ANN imitator for 1 step prediction steady state performance with a 325 V reference amplitude and R_{load} = 60 Ω. THD = 1.356%

- Figure 5 illustrates the excellent transient performance of the ANN imitators.
- Figure 6 shows the robustness of the ANN imitators to changes in reference voltage frequency.

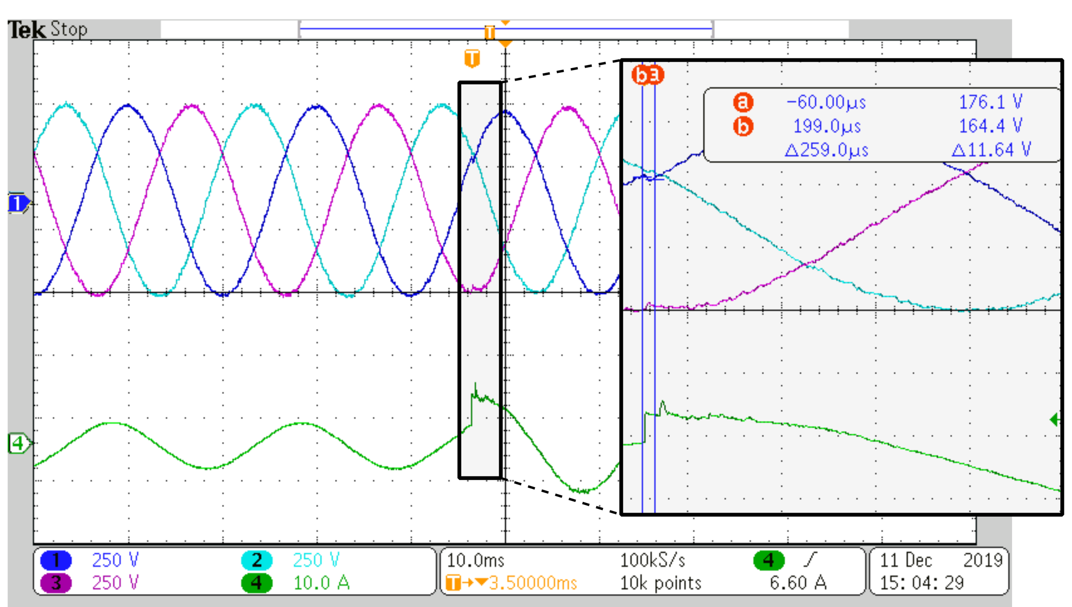

Fig. 5: Load step transient response for the 1-step imitator.

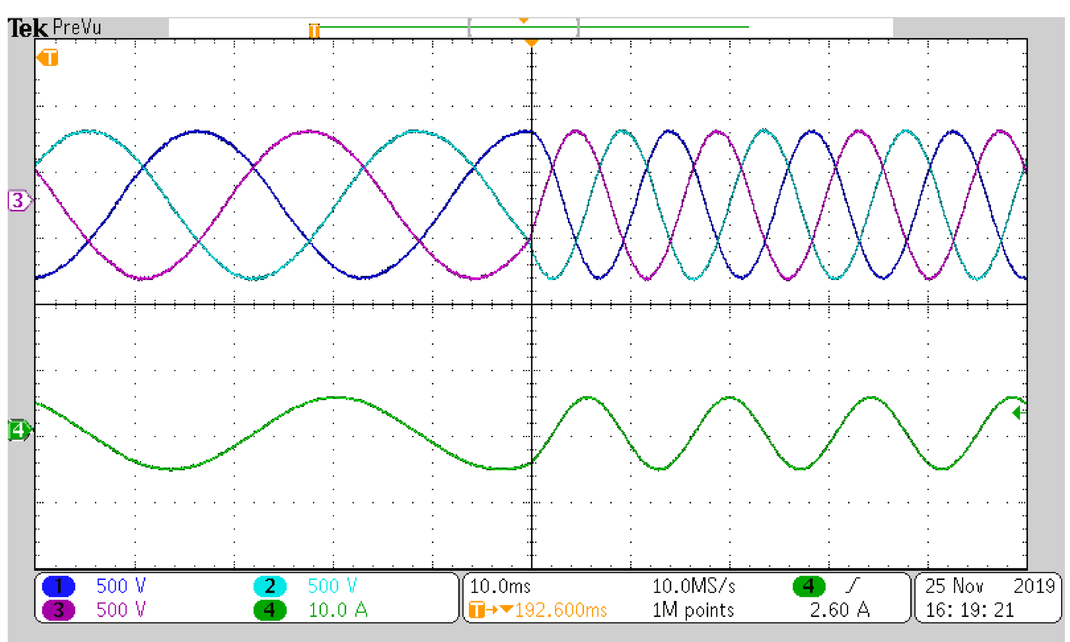

Fig. 6: Frequency step from 30 to 70 Hz for the 1-step imitator.

- The same training process and experimental validation is performed for 2 and 3 steps FS-MPC, with comparable experimental results.
- The ANN imitators are able to extrapolate to data points for which they have not been trained, being able to track voltage references with different frequencies and amplitudes.