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Hysteresis Modeling in Iron-Dominated Magnets based on a Deep Neural Network Approach

RESEARCH ACTIVITY CONTEXT

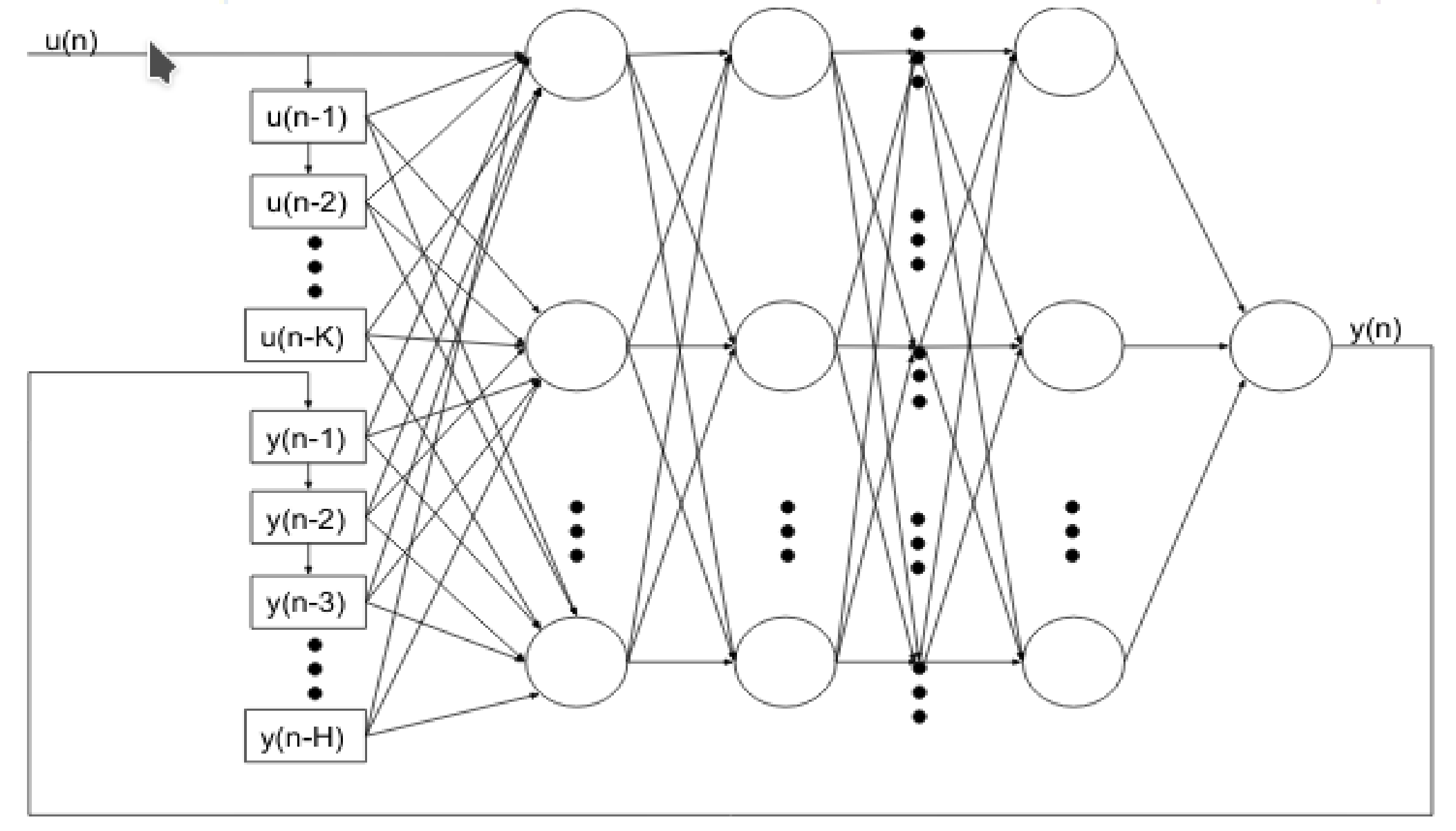
Modeling of quasi-static and dynamic hysteresis loops is one of the most challenging topics in compu-tational magnetism, mainly due to the strong non-linearity and history dependency shown by ferromagnetic materials. The complex excitation current waveforms I(t), used in particle accelerators (PAs) are still an open focus of scientific interest because B(I) becomes much more complex and hard to predict. In PAs, the beam is accelerated by radio frequency cavities which generate a bending field, increasing in proportion to thebeam momentum. Accurate knowledge of the magnetic field B(t) at any given time during a magnetic cycle is critical for beam control, power supply control, beam diagnostics, and qualitative feedback tooperators. The required accuracy is typically 0.01%.

I worked on tuning a deep neural network to fit directly the magnet response, by avoiding complementary physical models.

NEURAL NETWORK ARCHITECTURE

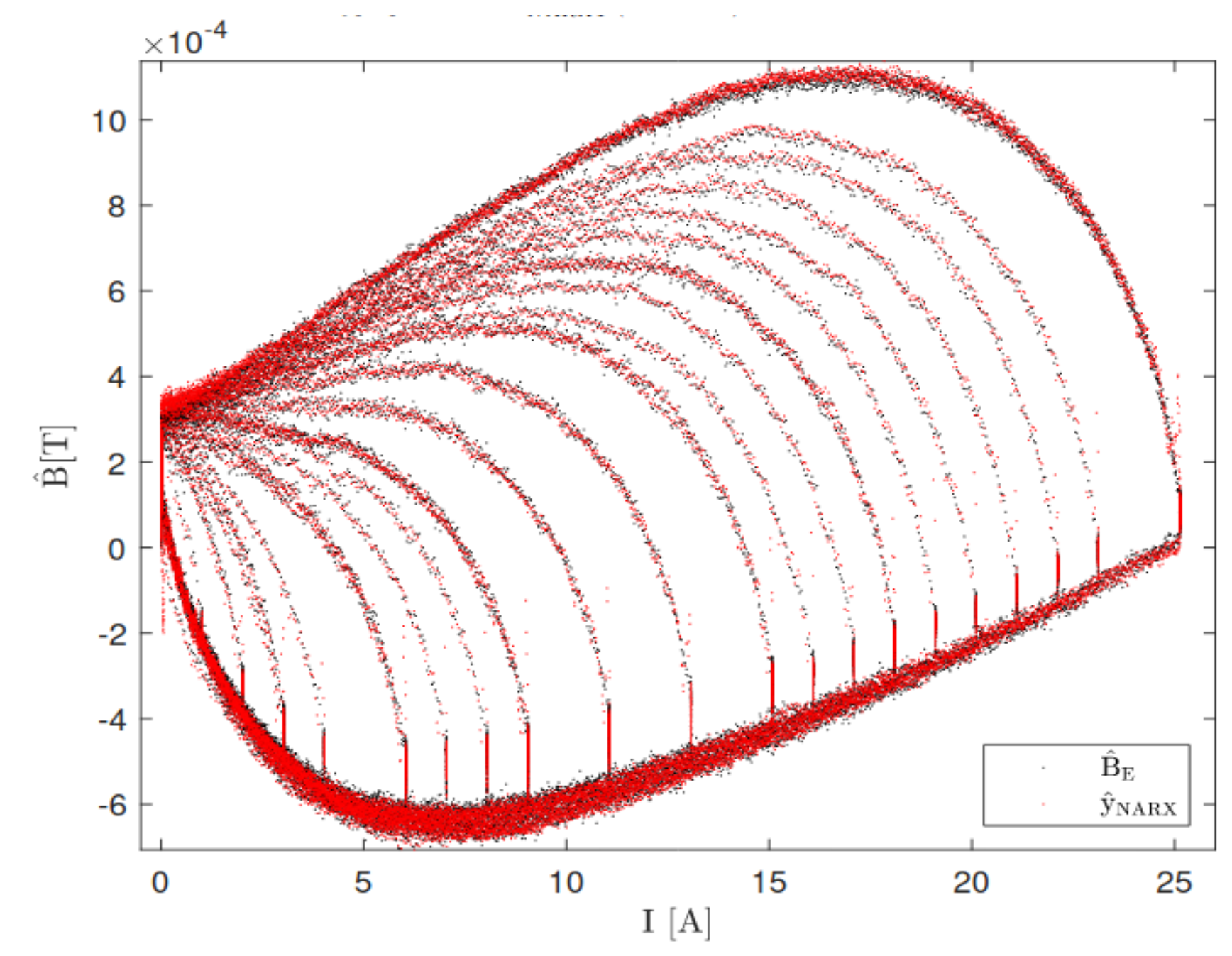
Different architectures are considered and selected according to a compromise betweenthe accuracy of the field estimation and the levelof complexity of the network. The best performing architecture results a *Nonlinear Autoregressive Ex-ogenous Neural Network* (NARX), Which reliesontemporal feedback to capture the underlying physics.The results of tests carried out on a dedicated experimental setup, taken as a re

$$a_j^1(n) = \phi^{A_1}\left(\sum_{h=1}^{H} W_{jh}^{O} y(n-h) + \sum_{k=0}^{K} W_{jk}^{I} u(n-k)\right)$$



RESULTS

The NARX networks achieve a bestcase NRMSE of 0.006%. Thanks to hav-ing memory of past outputs, the NARX networks are shown to be able to reconstruct very accurately the dynamic b



$$RMSE(y_i, D^{test}) = \sqrt{\frac{\sum_{n\in N}(y_i(n) - B^{test}(n))^2}{|N|}} \quad NRMSE(y, D_E) = \frac{RMSE(y, D_E)}{B_{max}} \cdot 100$$

CONCLUSIONS

We tested our network on the raw datasets. We found that NARX networks achieve in general the required level of performance i.e. an NRMSE better than 0.01%. Such excellent performance paves a very promising way for future applications in this context.

COLLABORATIONS

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FUTURE WORK

The plans for the future are to train and test NARX networks on awider variety of excitation waveforms, such as e.g. sequences of cycles with flat-tops increasing or decreasing randomly, which are representative of the most challenging actual operating conditions of accelera-tor magnets. As part of therenovation of the real-timemagnetic measurement systems currently ongoing at CERN, weare implementing in FPGA hardware a real-time version of the NARX networks that will be able to carry out a continuous field prediction, in parallel to the measurements.

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