Project **RUBY**

Robust and reliable general management tool for performance and durability improvement of fuel cell stationary units

FUEL CELL STATE OF HEALTH FORECASTING USING ECHO STATE NETWORKS

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Context

Echo State Networks

Designed approach

Analyze of results

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Context

Limitation → Lifetime of fuel cells

DOE objectives

2020 : 40 000h Stationary / 5000h Vehicle

Ultimate : 80 000h / 8000h

Tools :

Diagnosis → Detection of degrading conditions

Prognosis → Forecasting future performance

↓

Control → Changes in operating conditions

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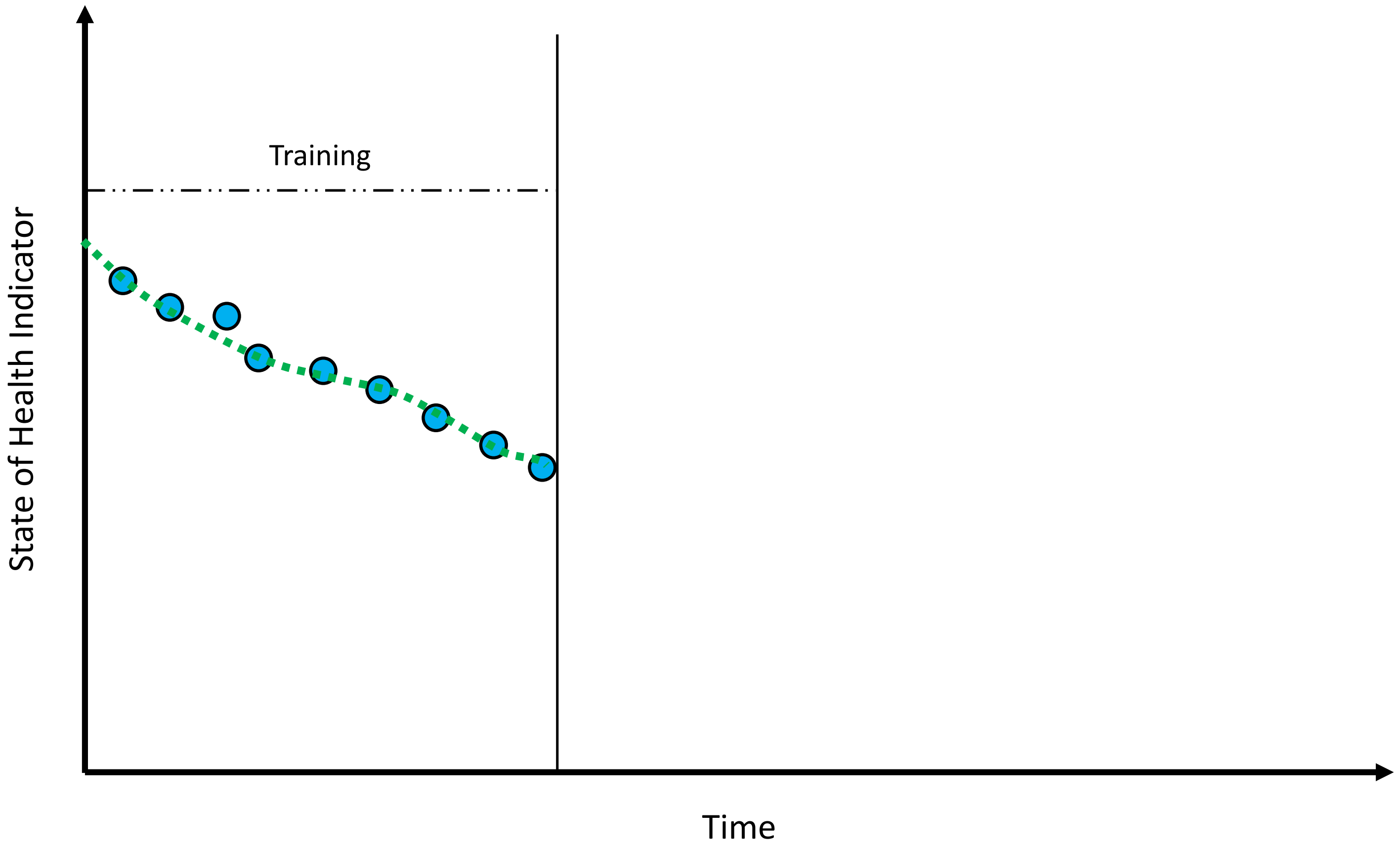
Prognosis principle



SoH indicator : e.g Stack voltage

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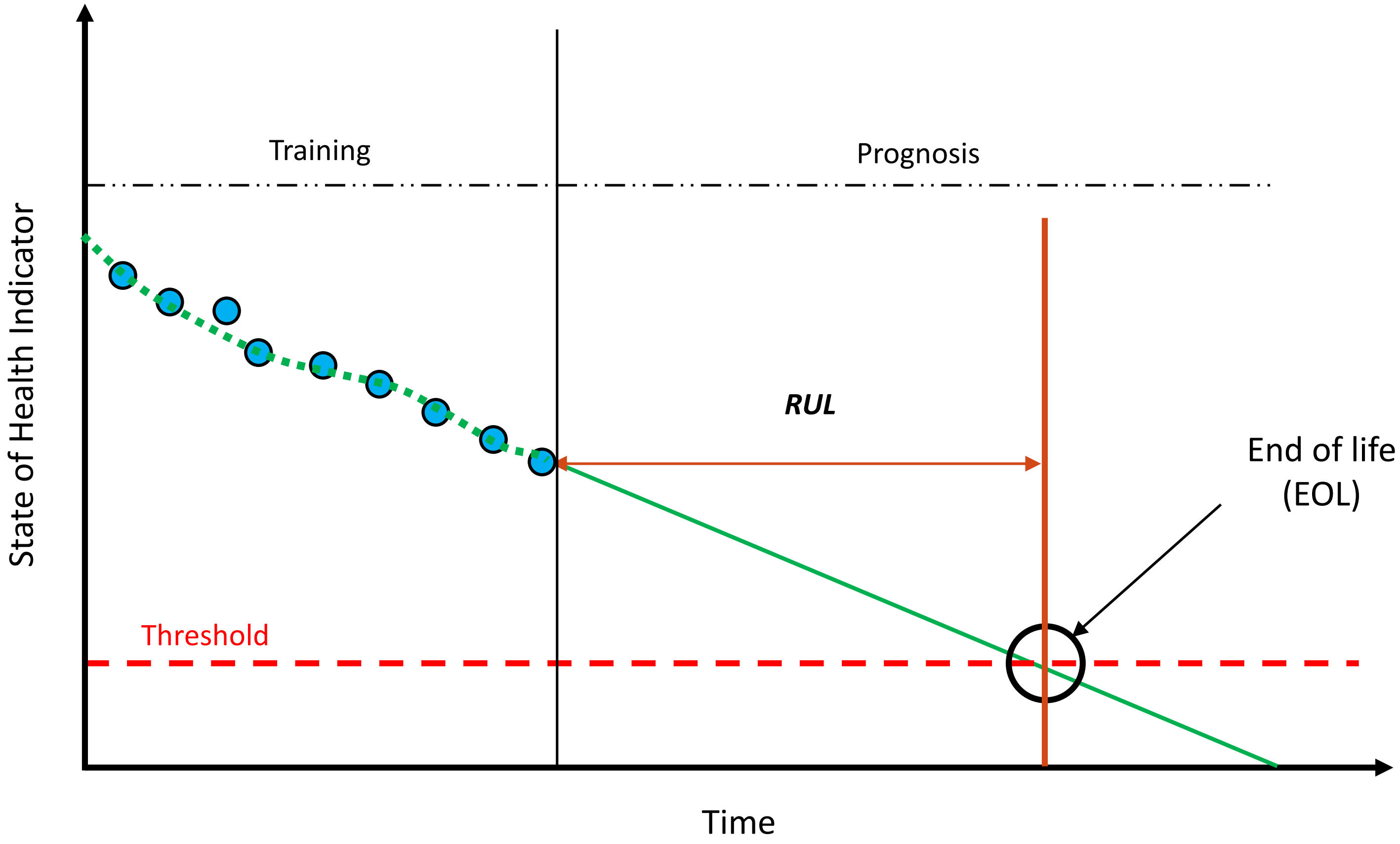
Prognosis principle



Evaluation of the algorithm

Mean square error

- $\sqrt{\frac{1}{n}\cdot\sum_{t=1}^{n}(erreur)^2}$

Percentage of mean absolute error

$$\frac{100}{n}\cdot\sum_{t=1}^{n}\left|\frac{Erreur}{vrai}\right|$$

Evaluation of prediction

Performing several iterations

Confidence interval

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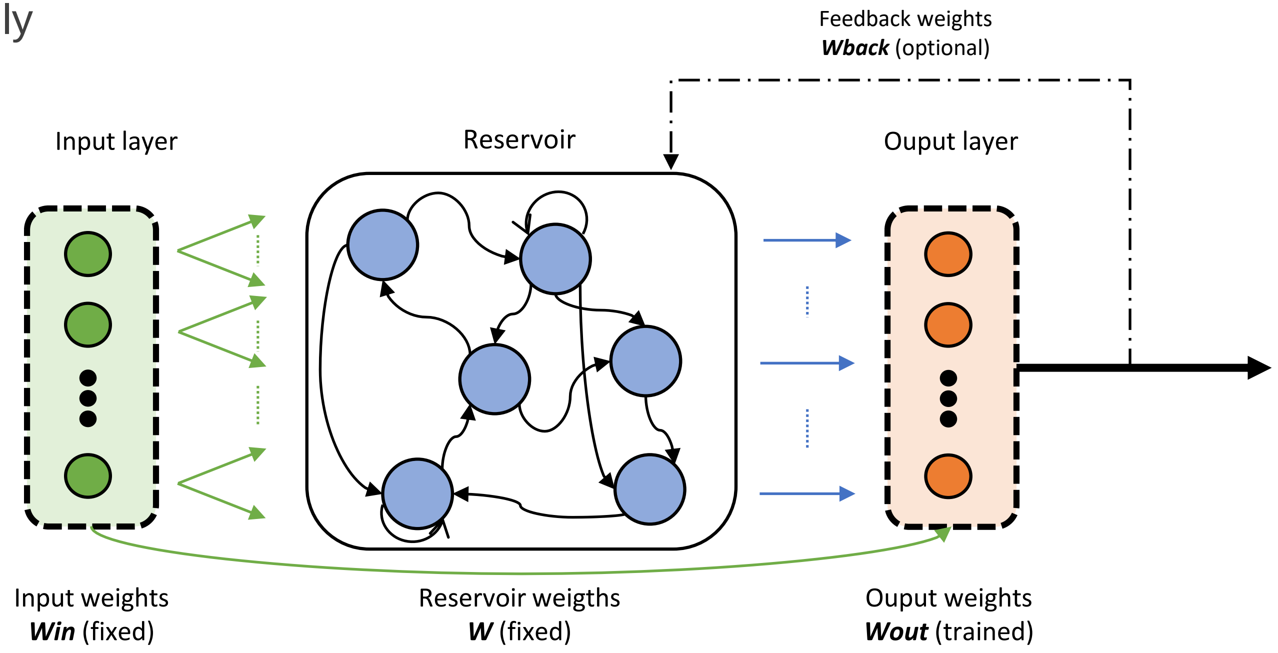
Echo State Network

Echo State Network :
- Development: 2000s by Herbert Jaeger
- Derived from RNN
  - Replacement of RNN layers by a reservoir
- Specificities :
  - Propagation of information in a high dimensional space
    - Data separation
  - Setting the weights of recurrent connections randomly
  - Drive the network with only the output weights



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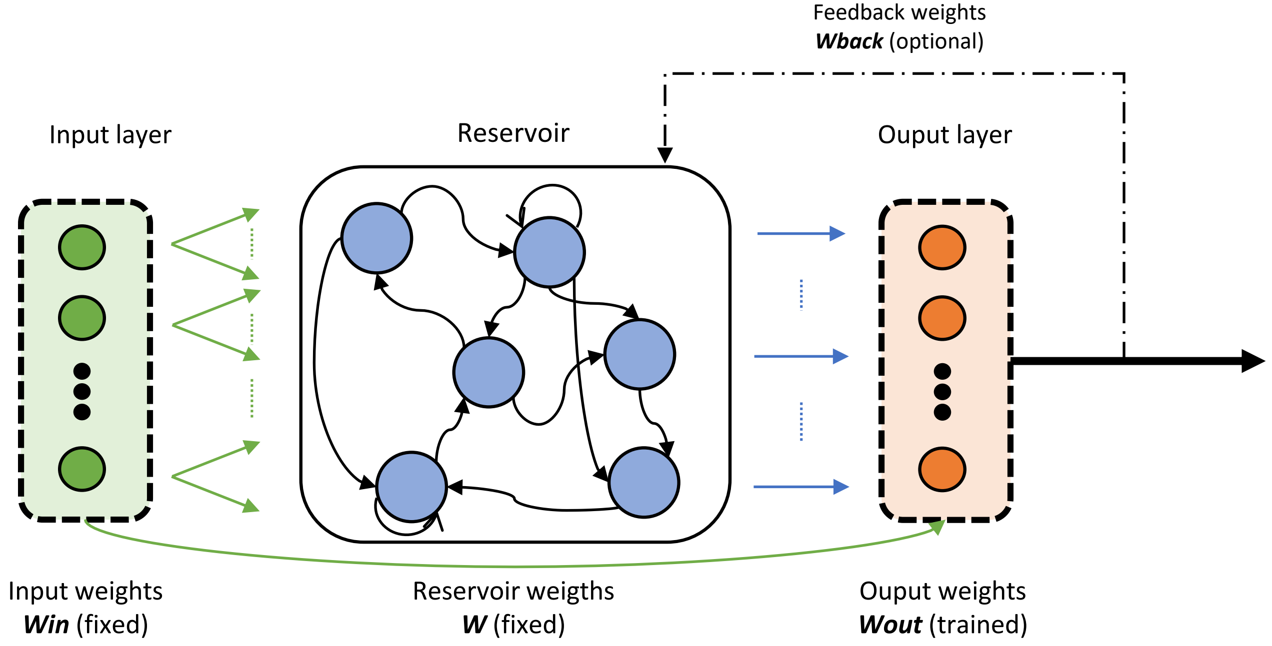
Echo State Network - ESN

ESN parameters

- Spectral radius
  - Matrix eigenvalue
  - Amplification of internal states as the network process information
  - High value → Strong amplification
- Leaky rate
  - Decay rate of information in the internal states over time
  - Low value → Retain mainly old information
- Connectivity
  - Percentage of non-zero weight in the reservoir matrix
  - Improves calculation times → Faster reservoir updates
  - Develops individual dynamics
- Number of neurons
  - Possibly very large > 1000 → Linear regression
- Initialization of weights
  - Random Uniform / Normal distribution



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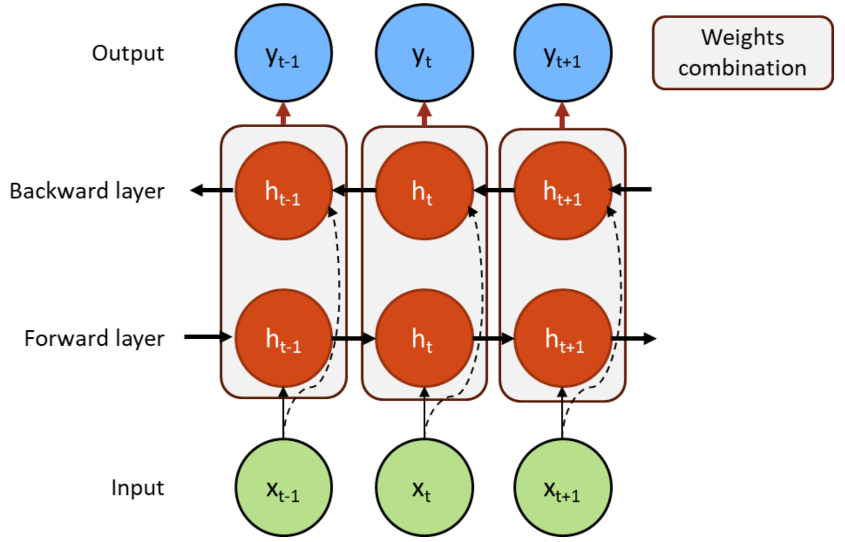
Bidirectional Echo State Network - ESN

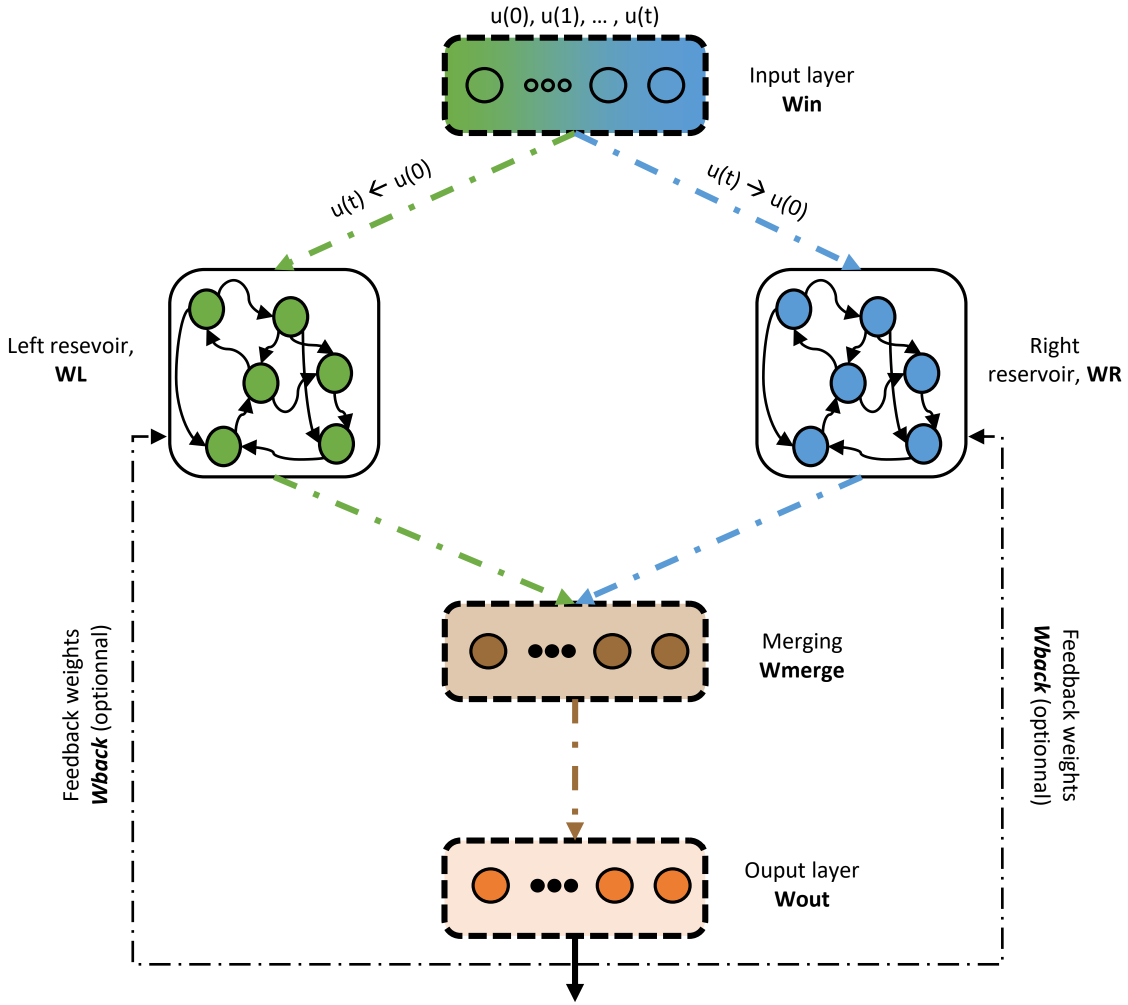
Limitations of ESN:

- Difficult to learn long term dependencies → Focus on last time steps
- Don't memorize the context

Solution: Bidirectional reservoir BiESN

- Double the number of reservoirs
- Sequence learning in chronological and reverse direction





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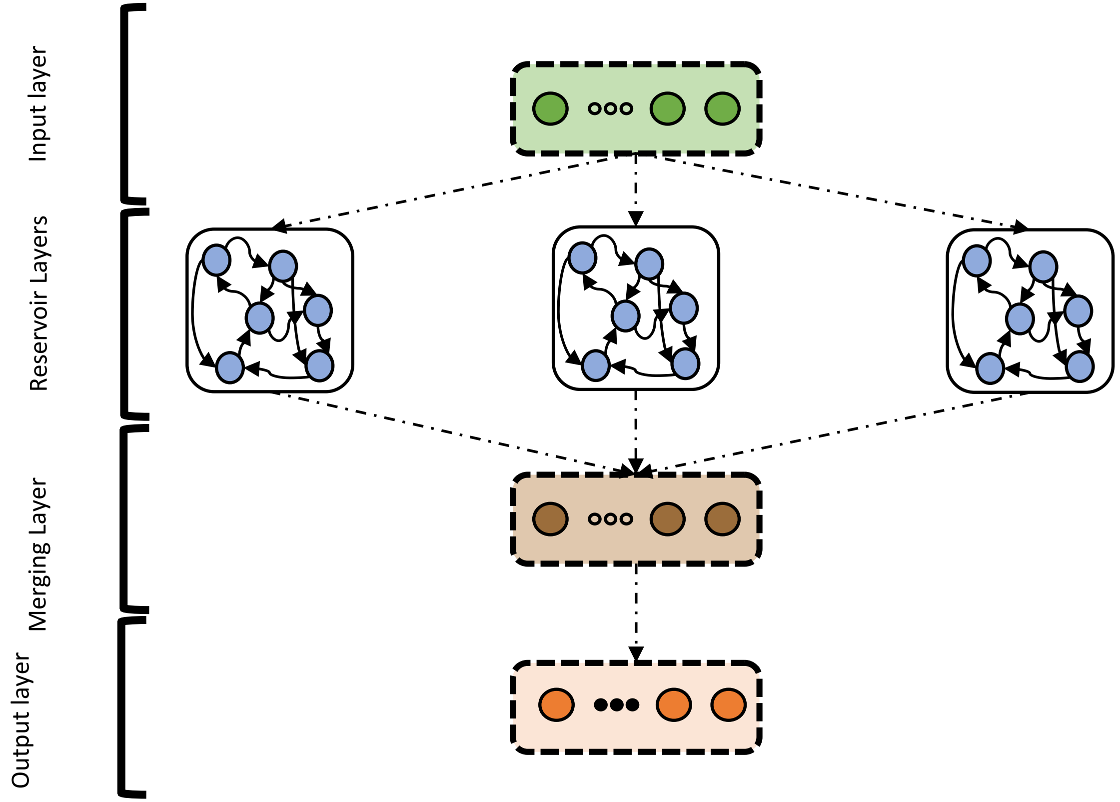
Multi-reservoir ESN

Limitation of ESN:

- Complexity to find good reservoir parameters

Solution: Multi-Reservoir :

- Use of reservoirs in parallel and/or in series
- Different parameters for each reservoir → more chances to capture the dynamics
- Decreasing burden of the parameter optimisation



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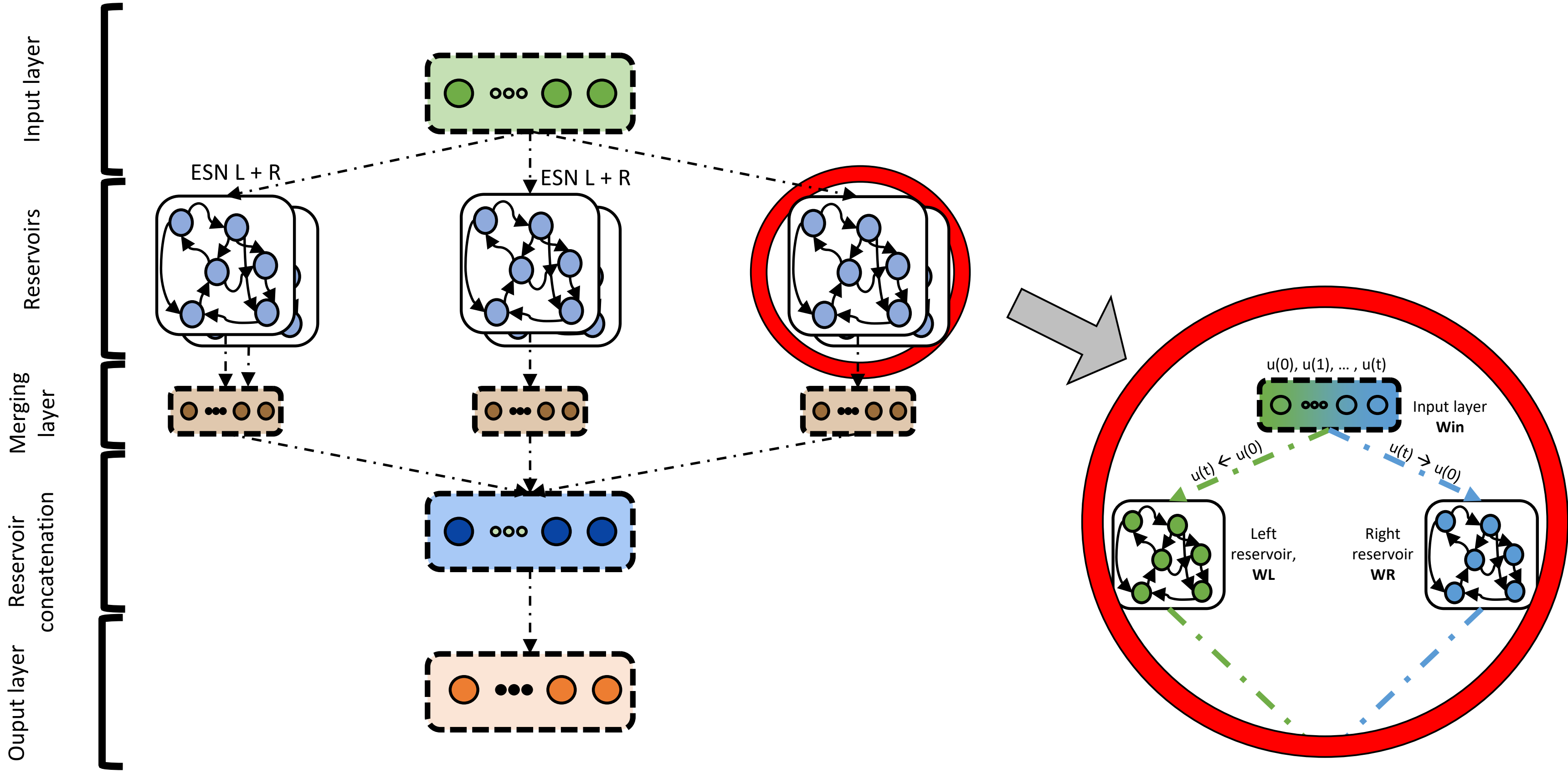
Designed approach - Network

ESN Multi-reservoir bidirectional

- 3 specialized bidirectional reservoirs: low, medium and high dynamics
  - Minimize reservoirs optimization
  - Maximizing detectable dynamics



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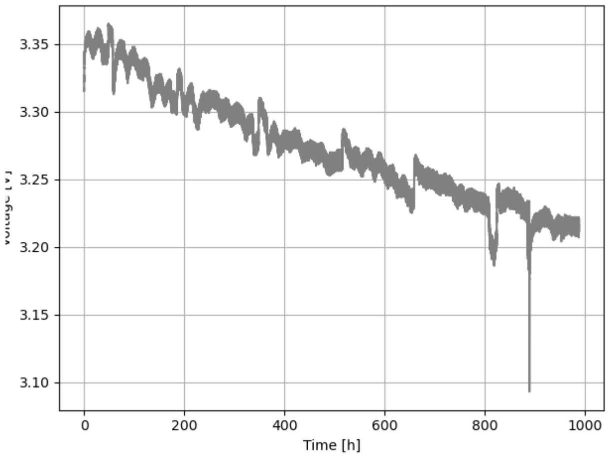
Designed approach - Database

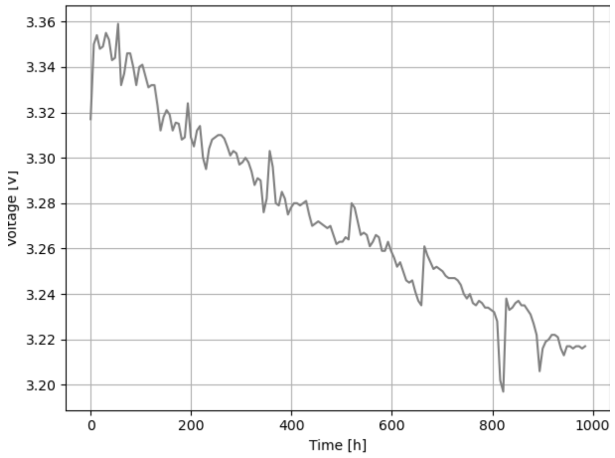
- From the 2014 IEEE PHM challenge → Open Database
- Long-term test (1000h) on two PEMFC-LT
    - 1st test: static state
        - Constant current 0.7 A/cm²
    - 2nd test: triangular current ripple
        - DC component 0.7 A/cm²
        - Triangular component 0.14 A/cm² peak to peak

- Only the static state is studied in this presentation
- Acquisition frequency: 1/30Hz
    - Choice to retain 1 pt / 6h with a rolling window → Only a trend is studied

Raw data



Data selected



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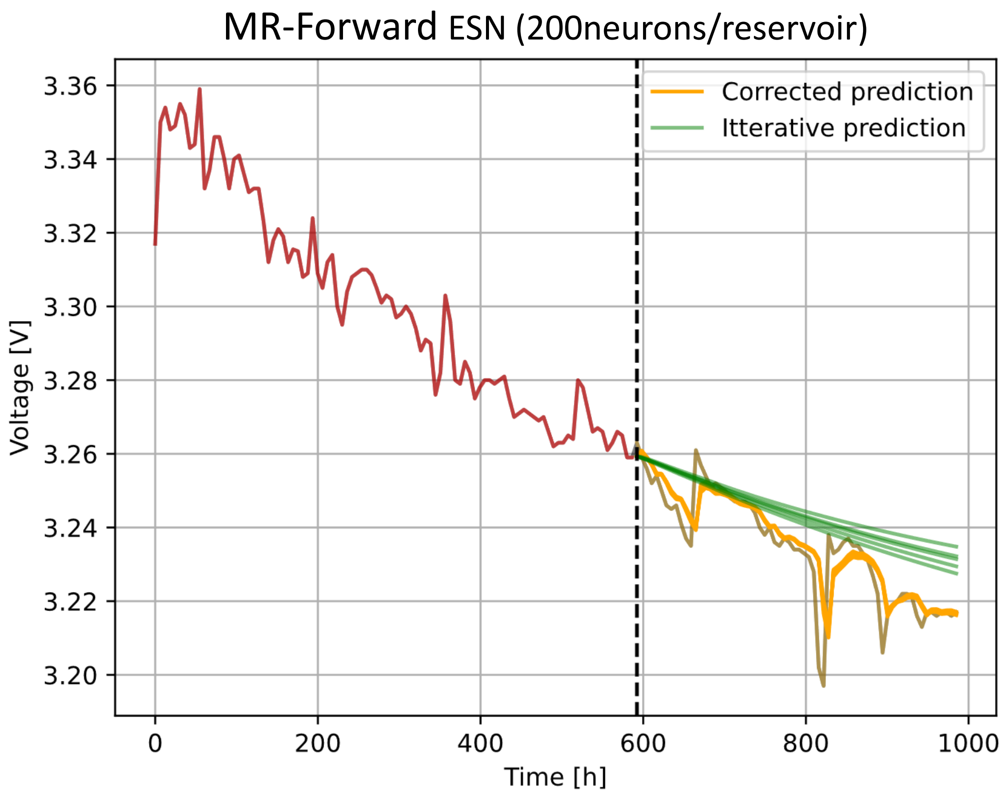
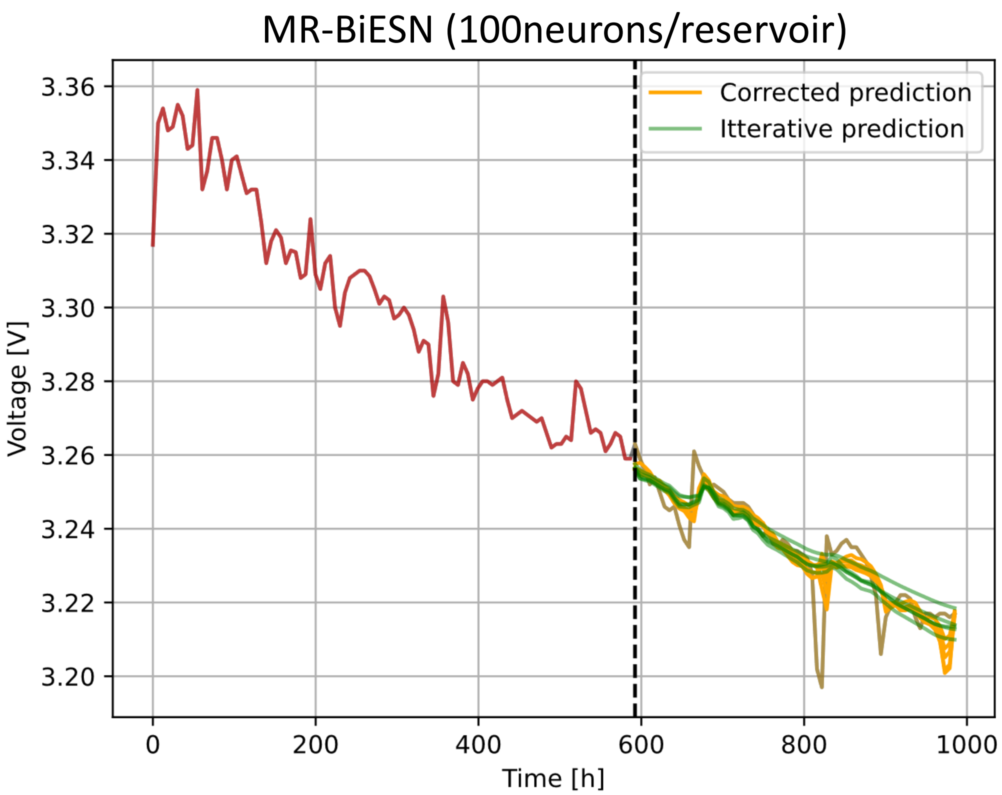
Results – Comparison with MR-Forward ESN





Corrected forecasting → Only predict next timestep → no bias

- MR-BiESN is slighty less able to predict the next timestep
  - Backward layer learn information on past history “less” relevant
- MR-Forward ESN is focus on last historical data
  - Correspond more to corrected forecasting as bias is not accumulated

Forward ESN ≥ Bidirectional ESN

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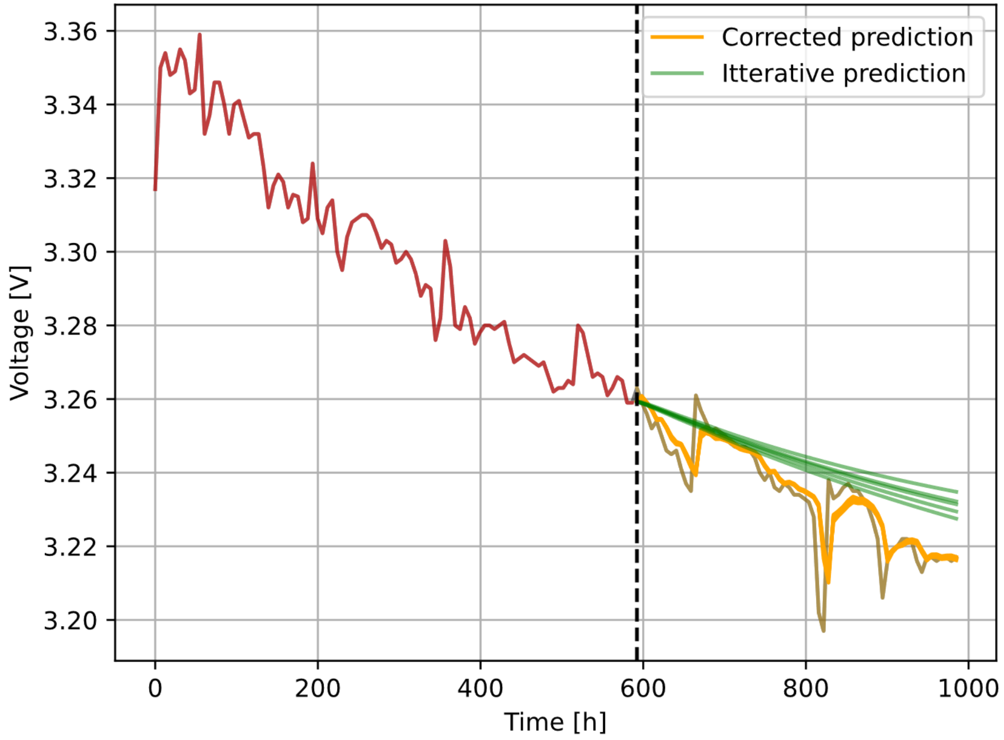
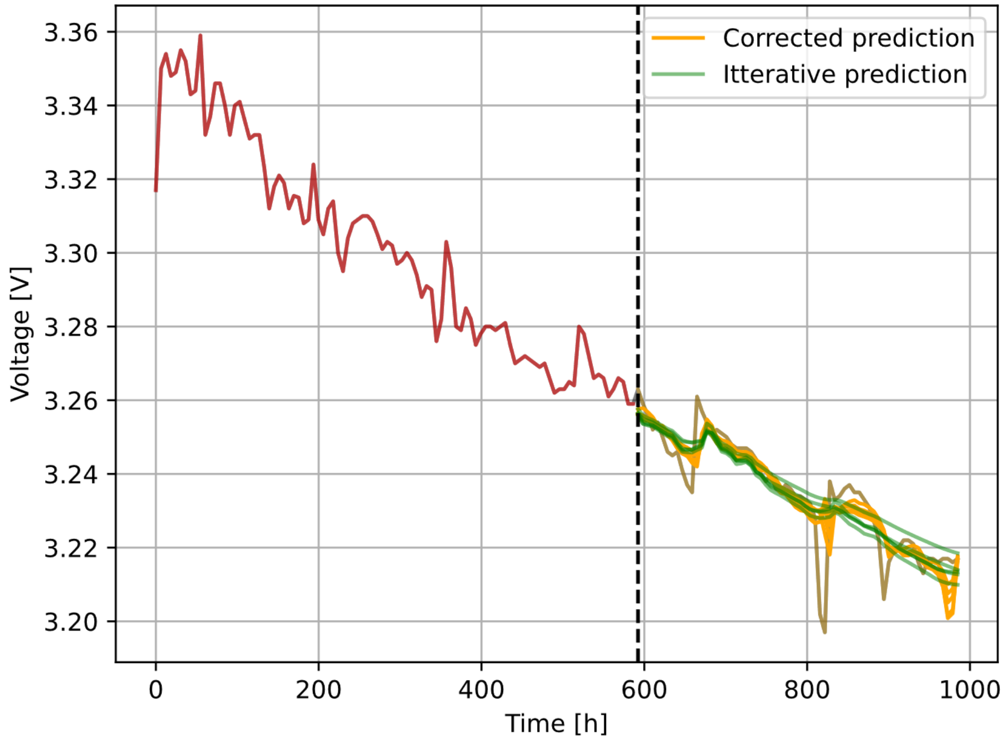
Results – Comparison with MR-Forward ESN

MR-Forward ESN (200neurons/ reservoir)



MR-BiESN (100neurons/ reservoir)



Iterative forecasting → prediction is used as new input

- MR-BiESN network catches periodic recovering process
  - Linear trend with recovering
- MR- One Way ESN catches only global trend

Bidirectional ESN >> Forward ESN

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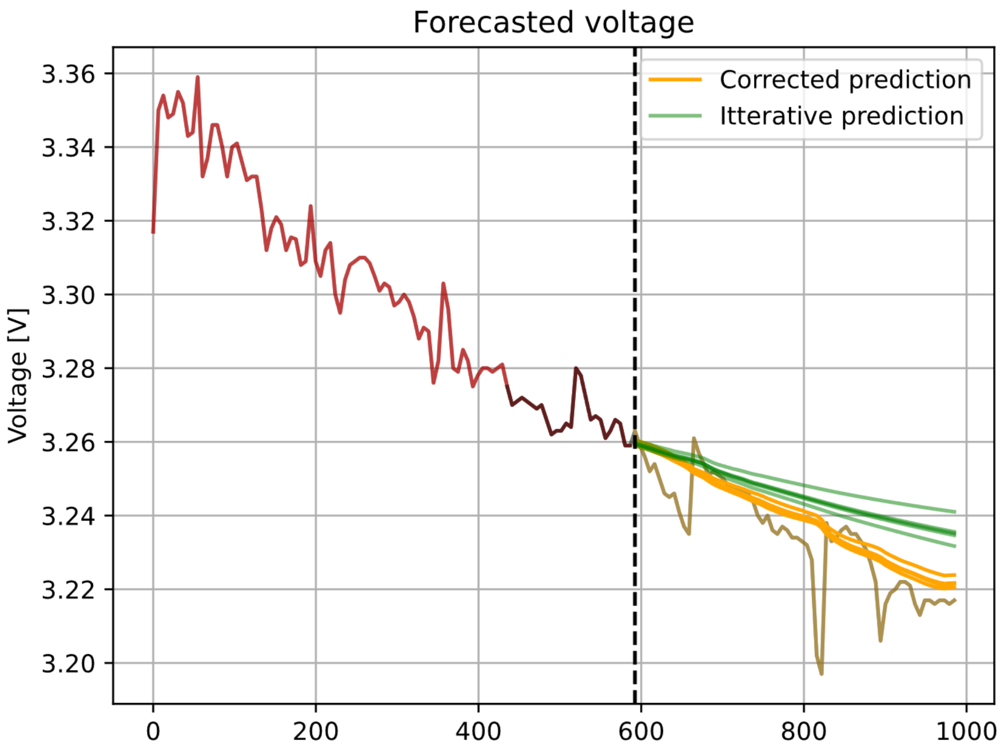
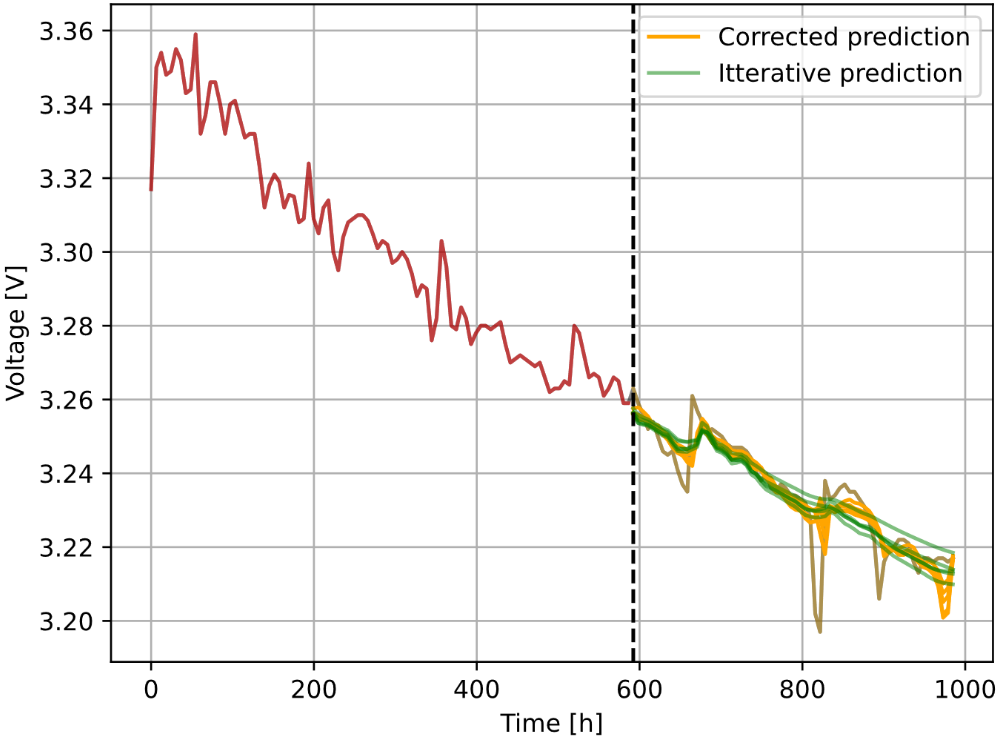
Comparison with BiLSTM

3 BiLSTM stacked (100neurons/reservoir)



MR-BiESN (100neurons/reservoir)



LSTM: 563 401 trainable parameters

- Need more iterations to converge (x3)
- Results seems underfit → underfitted
- Lack of data

MR-BiESN network: 601 trainable parameters

- Better performances for small dataset

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Conclusion

- Synthesis:
  - Principle of Echo State Networks
  - Prognostic approach based on data only
  - Study case on a fuel cell
- Designed approach advantages
  - Dynamics correctly captured
  - Better performances than BiLSTM for small databases --> Most used Network for forecasting
  - Ability to improve by re-optimizing with recent data
  - Can be applied to many systems
- Future prospect:
  - Generalization of the method with other databases

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