Neural Network Approach for Predicting Drum Pressure and Level in a Coal-fired Subcritical Power Plant

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Outline

- Background
- Boiler Drum Data
- NARX Model
- NARX Model Training
- Results
- Conclusion and Future Work
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Layout of Coal-fired Subcritical Power Plant
Boiler Drum is a critical component of a coal-fired subcritical power plant:

- acts as energy reservoir in the plant enabling it to cope with short term load changes
- dictates overall plant dynamics due to the slower dynamics compared to the steam turbine dynamics

Due to tightening regulations, deserves study of the dynamics for operation and control purposes

Data-based approach such as neural networks less laborious than physical modelling
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Boiler Drum Process

- Represented by a detailed first principle model according to Åström and Bell [3] using gPROMS tool.
  - Inputs: Feedwater flowrate, Steam flowrate and heat energy input
  - Outputs: Drum pressure and drum water level

- Thermodynamic properties of water/steam were obtained using IAPWS-95 formulation in Aspen Properties via COThermo interface.

- Thermodynamic property derivatives were obtained using polynomial approximations of steam table calculations from NIST REFPROP V9.1.
Global Conservation Equations

\[
\frac{d}{dt} [\rho_s V_{st} + \rho_w V_{wt}] = m_{fw} - m_{st}
\]

\[
\frac{d}{dt} [\rho_s h_s V_{st} + \rho_w h_w V_{wt} - p V_t + M_r C_p T_{sat}] = Q + h_{fw} m_{fw} - h_s m_{st}
\]

\[V_{st} + V_{wt} = V\]

Drum Dynamics

\[
\frac{d}{dt} \rho_s V_{sd} = \alpha_r m_r - m_{sd} - m_{cd}
\]

\[m_{sd} = \frac{P_r}{T_d} (V_{sd} - V_{sd}^0) + \alpha_r m_{dc} + \alpha_r \beta (m_{dc} - m_r)
\]

\[V_{wd} = V_{wt} - V_{dc} - (1-\overline{\alpha_v}) V_r\]

\[m_{cd} = m_{fw} \frac{h_w - h_{fw}}{h_s - h_w} + \frac{1}{h_s - h_w} [\rho_s V_{sd} \frac{dh_s}{dt} + \rho_w V_{wd} \frac{dh_w}{dt} - (V_{sd} + V_{wd}) \frac{dp}{dt} + m_d C_p \frac{dT_{sat}}{dt}]\]

\[L_d = \frac{V_{wd} + V_{sd}}{A_d}\]

Downcomer-Riser Dynamics

\[
\frac{d}{dt} [\rho_s \overline{\alpha_v} V_r + \rho_w (1-\overline{\alpha_v}) V_r] = m_{dc} - m_r
\]

\[
\frac{d}{dt} [\rho_s h_s \overline{\alpha_v} V_r + \rho_w h_w (1-\overline{\alpha_v}) V_r - p V_r + M_r C_p T_{sat}] = Q + m_{dc} h_w - (\alpha_r (h_s - h_w) + h_w) m_r
\]

\[\overline{\alpha_v} = \frac{\rho_w}{\rho_w - \rho_s} [1 - \frac{\rho_s}{\alpha_r (\rho_w - \rho_s)} ln(1 + \alpha_r \frac{\rho_w - \rho_s}{\rho_s})]\]

\[m_{dc} = \sqrt{\frac{2g \rho_w \overline{\alpha_v} A_d V_t (\rho_w - \rho_s)}{k}}\]
Boiler Drum Data

- Data obtained at open loop conditions using the developed model.
- The system is excited by perturbing the inputs in succession with a series of step changes in no particular order.
- Perturbation in each input is sustained for an hour resulting to a total test period of 3 hours (10800 seconds).
- Other inputs are maintained at their equilibrium value while perturbing the other.
Boiler Drum Data

Drum water level (m)

Drum Pressure (Pa)

Time (s)
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Neural Networks (NNs)

- Computational paradigm inspired from the structure of biological neural networks and their way of encoding and solving problems.

- Able to identify underlying highly complex relationships based on input-output data only.
Neural Networks (NNs)

- NN model capable of reproducing time-dependent (dynamic) data takes into account the time variable by means of a memory process.

- This is done using NN architectures with feedback connections among neurones and time delay lines (TDL).

- NARX NN is a typical NN with feedback connections enclosing several layers of the network and a TDL.
NARX Model

NARX Model is defined by the Equation:

\[ y(t) = f[y(t-1), y(t-2), ..., y(t-n_y), u(t-1), u(t-2), ..., u(t-n_u)] \]
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NARX Model Training

- Training complicated due to the feedback loop; ideally dynamic training algorithm which is complex is needed.

(a) Parallel Architecture
(Standard NARX Architecture)

(b) Series-Parallel Architecture

- With (b), less complex static training algorithm is used for training.
- Training with simulated data from the detailed physical model.
- Early stopping technique used to avoid overfitting: Data divided into training (70%), validation (15%) and testing (15%) data.
- Levenberg-Marquardt training algorithm used (*trainlm*) with mean squared error (MSE) performance function.
- 100 neurones in the hidden layer each with a sigmoid transfer function.
NARX Model Training

\[ \text{MSE} = \frac{1}{N} \sum_{i=0}^{N} (z_i - y_i)^2 \rightarrow \text{min} \]

Best Validation Performance is 4.8725e-07 at epoch 300

Mean Squared Error (mse)
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The plots show reliable estimate of the network parameters, weights and biases.
Results

Output/Target Comparison (Drum Pressure)

Output/Target Comparison (Drum Level)
Results

Step Change Test: Performed on one input at a time while other inputs remain unchanged

+30 kg/s step change in feedwater flowrate
Results

+10 MW step change in Heat Input

- Drum Level (m)
  - Time (s)
  - Actual
  - NARX

- Drum Pressure (Pa)
  - Time (s)
  - Actual
  - NARX
Results

+10 kg/s step change in Steam Flowrate
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Conclusion and Future Work

- NARX NN can be used to obtain reliable dynamic model of a boiler drum from the plant input-output operating data only.

- Use of NARX NN avoids the rigours of reliable parameter estimation often needed in modelling from first principle.

- As it is the case with all empirical models, NARX NN models are only reliable when they are used within the conditions that they were trained.

- The NARX NN model developed in this study is subject to the inherent deficiencies in Åström and Bell [3] model which was used to obtain the training data.

- Development of model predictive control (MPC) of the boiler drum based on the NARX NN model is on-going.
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2) Åström, K.J. and Bell, R.D. Drum-boiler dynamics. Automatica 2000; 36: 363-378.
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Questions???

Thank you for your Attention!

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