# Machine-Learning Techniques to Protect Critical Infrastructure From Cybersecurity Incidents or Equipment Incidents

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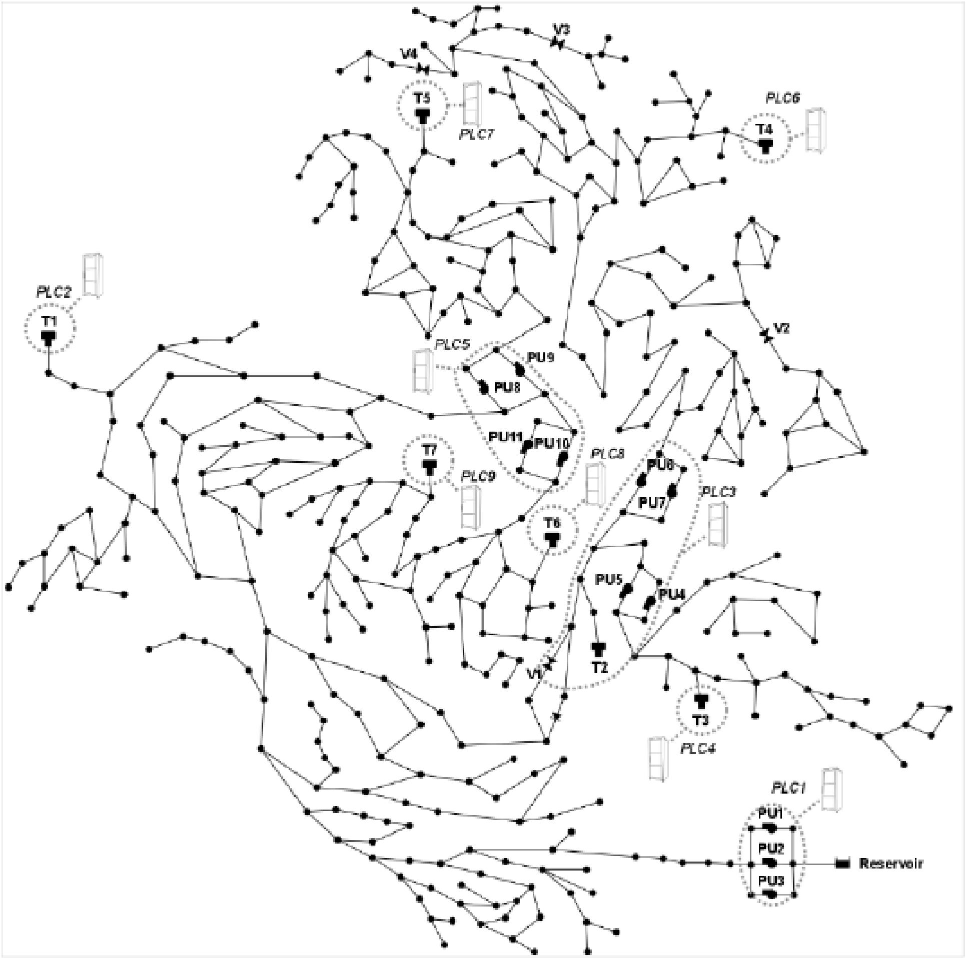
# Agenda

- Challenge Introduction and Goal
- Data Source
- Exploratory Data Analysis and Feature Engineering
- Solution Design
- Unsupervised Learning Approaches
- Implementation
- Anomaly Detection Results
- Conclusion

# Problem Introduction

- Industrial control system cybersecurity remains a critical challenge
- Goal: detect cyber attacks on the industrial control system supporting water distribution
- Illustrate the machine learning (ML) design processes involved in solving this challenge



# Data Source

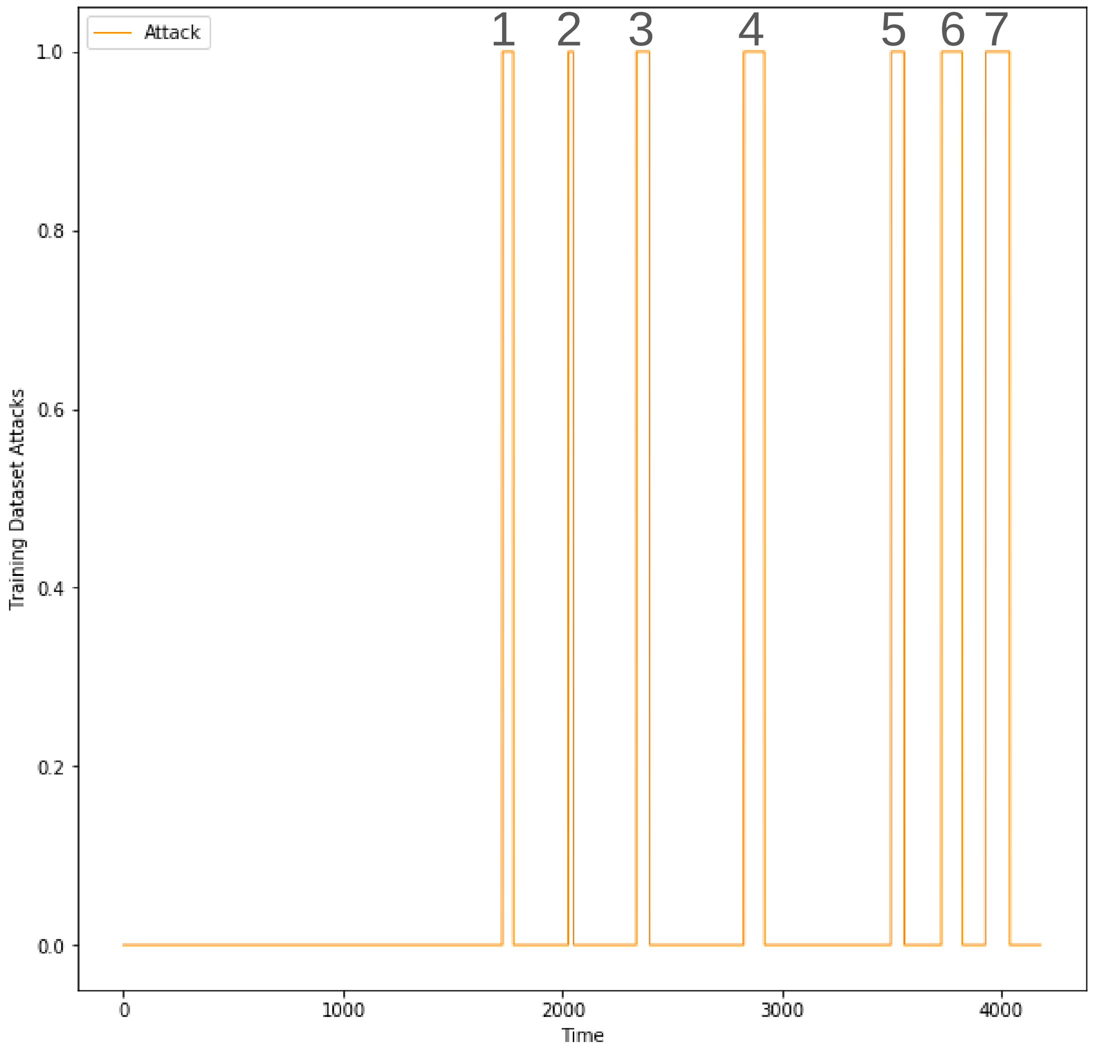
- **Data from the Battle of the Attack Detection Algorithms (BATADAL) - https://batadal.net/**
- **Scenario based upon a cyber attack on a water distribution system**
- **Normal system performance data provided**
- **3 datasets provided**
  - Normal operation (8,761 rows)
  - Under attack, available for training (4,177 rows)
  - Under attack, not available for training (2,089 rows)

# Data Set Sample

| DATETIME | L_T1 | L_T2 | L_T3 | L_T4 | L_T5 | L_T6 | L_T7 | F_PU1 | S_PU1 | F_PU2 | S_PU2 | F_PU3 | S_PU3 | F_PU4 | S_PU4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 06/01/14 00 | 0.50973 | 2.049003 | 3.191145 | 2.792634 | 2.656091 | 5.316831 | 1.562321 | 98.99844 | 1 | 99.01815 | 1 | 0 | 0 | 35.53669 | 1 |
| 06/01/14 01 | 0.41258 | 2.009072 | 3.642565 | 2.831673 | 3.126387 | 5.494855 | 1.852043 | 99.0959 | 1 | 99.11564 | 1 | 0 | 0 | 34.45491 | 1 |
| 06/01/14 02 | 0.320112 | 1.986093 | 4.140192 | 3.256733 | 3.574601 | 5.5 | 2.246126 | 98.42096 | 1 | 98.4405 | 1 | 0 | 0 | 33.48709 | 1 |
| 06/01/14 03 | 0.332879 | 2.009203 | 4.673478 | 3.744497 | 3.952379 | 5.5 | 3.203573 | 97.57517 | 1 | 97.59446 | 1 | 0 | 0 | 32.58554 | 1 |
| 06/01/14 04 | 0.483496 | 2.089049 | 5.237937 | 4.409456 | 3.504676 | 5.5 | 4.439714 | 97.35106 | 1 | 97.37028 | 1 | 0 | 0 | 31.46968 | 1 |
| 06/01/14 05 | 0.791114 | 2.773177 | 5.155802 | 3.937262 | 3.191528 | 5.322743 | 3.988906 | 94.13547 | 1 | 94.15375 | 1 | 0 | 0 | 0 | 0 |
| 06/01/14 06 | 1.186589 | 3.536068 | 4.983953 | 3.018011 | 2.859591 | 5.066728 | 2.977463 | 95.258 | 1 | 95.27661 | 1 | 0 | 0 | 0 | 0 |
| 06/01/14 07 | 1.420449 | 3.872926 | 4.747458 | 3.581882 | 2.359944 | 5.152646 | 2.953742 | 96.94746 | 1 | 96.96656 | 1 | 0 | 0 | 0 | 0 |
| 06/01/14 08 | 1.534827 | 4.138434 | 4.417932 | 3.959265 | 1.748313 | 5.395835 | 3.228596 | 96.97029 | 1 | 96.9894 | 1 | 0 | 0 | 0 | 0 |
| 06/01/14 09 | 1.576541 | 4.50004 | 4.130157 | 4.232002 | 1.666737 | 5.5 | 3.628678 | 97.15647 | 1 | 97.17564 | 1 | 0 | 0 | 0 | 0 |
| 06/01/14 10 | 1.55855 | 4.96201 | 3.665213 | 2.962582 | 2.107416 | 5.5 | 3.445807 | 97.81398 | 1 | 97.83334 | 1 | 0 | 0 | 0 | 0 |

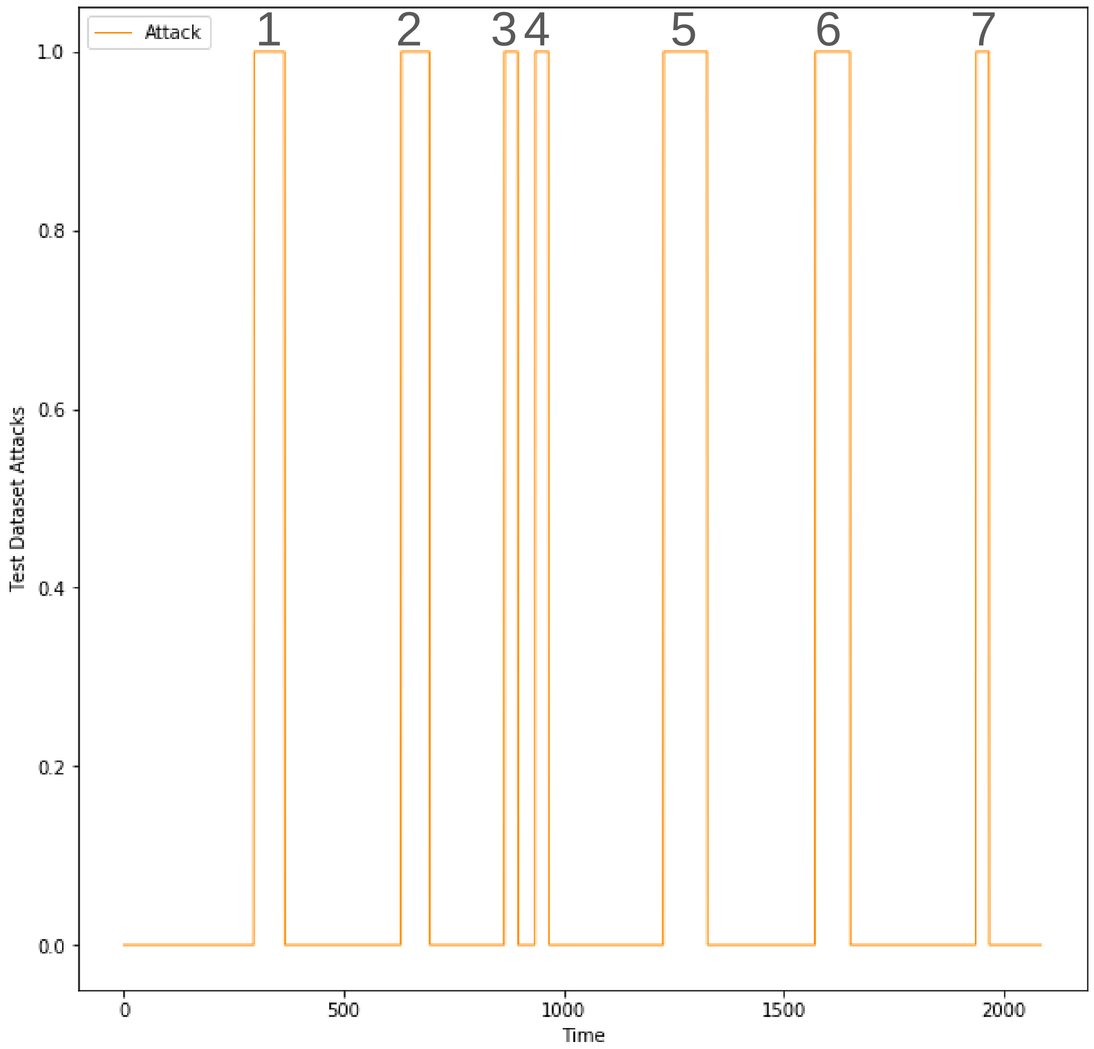
- **Each data set includes 43 input features representing:**
  - Tank levels
  - Pump switches
  - Pump flow rates
  - Valve positions
  - Valve flow rates
  - Pressures at various sensors

# Attacks Conducted –Training Dataset




1. Replay attack on tank 7 level
2. Replay attack on tank 7 level and pumps 10 and 11 flow and status
3. Alter tank 1 level readings causing pumps 1 and 2 to remain on and tank 1 overflow
4. Same as attack 3
5. Speed of pump 7 reduced causing low water levels in tank 4
6. Similar to attack 5 but increased speed reduction
7. Same as attack 6

# Attacks Conducted – Test Dataset




1. **Replay attack on tank 3 level and pump 4 and 5 flow and status**
2. **Attack alters tank 2 levels causing tank 2 to overflow**
3. **Activates pump 3**
4. **Similar to attack 3**
5. **Similar to attack 2**
6. **Replay attack on tank 7 level and pumps 10 and 11 flow and status**
7. **Manipulation of tank level signal leading to overflow of tank 6**

# Exploratory Data Analysis

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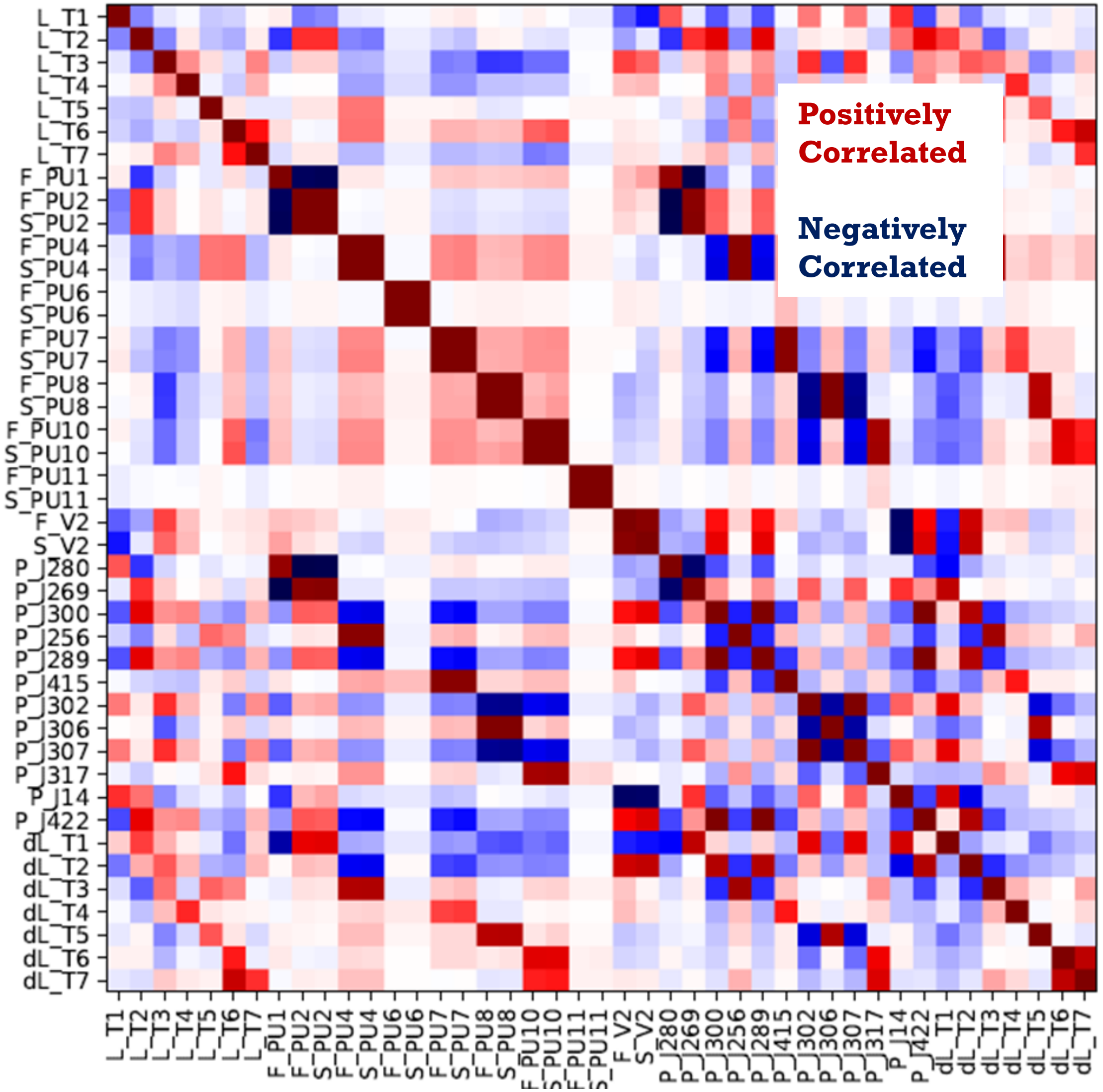
- Notable correlations
  - Correlation between pump switch and flow
  - Negative correlation between pump 1 and 2 flows
  - Correlation between tanks 6 and 7
  - Correlation between tank 3 and pump 4

- In some situations, it is useful to remove highly-correlated data
  - Breaking of a correlation might indicate an attack so they are left in
- Pump 1 is in constant use
- Pumps 3, 5, and 9 are never used
- Pumps 6 and 11 are rarely used

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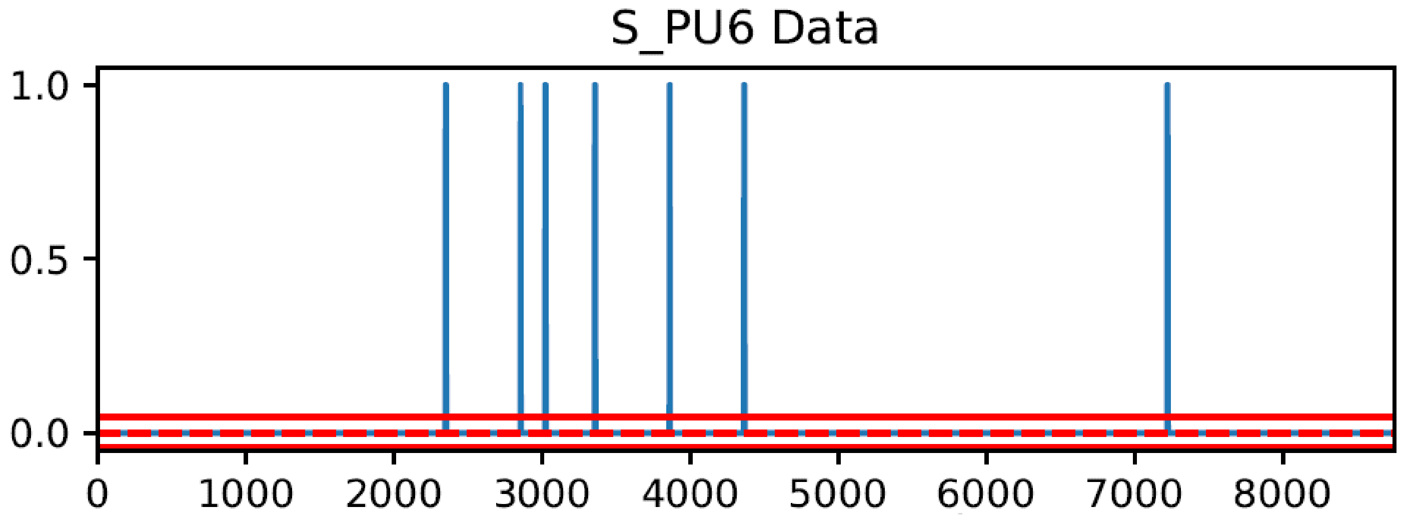
# Feature Engineering – Sparse Features

- **Some of the data elements have significant outliers**
  - Due to only occasional equipment use
- **These can cause very high values in the normalized data and negatively impact training**
- **Solutions include limiting the magnitude of the normalized values or not normalizing these type of features**

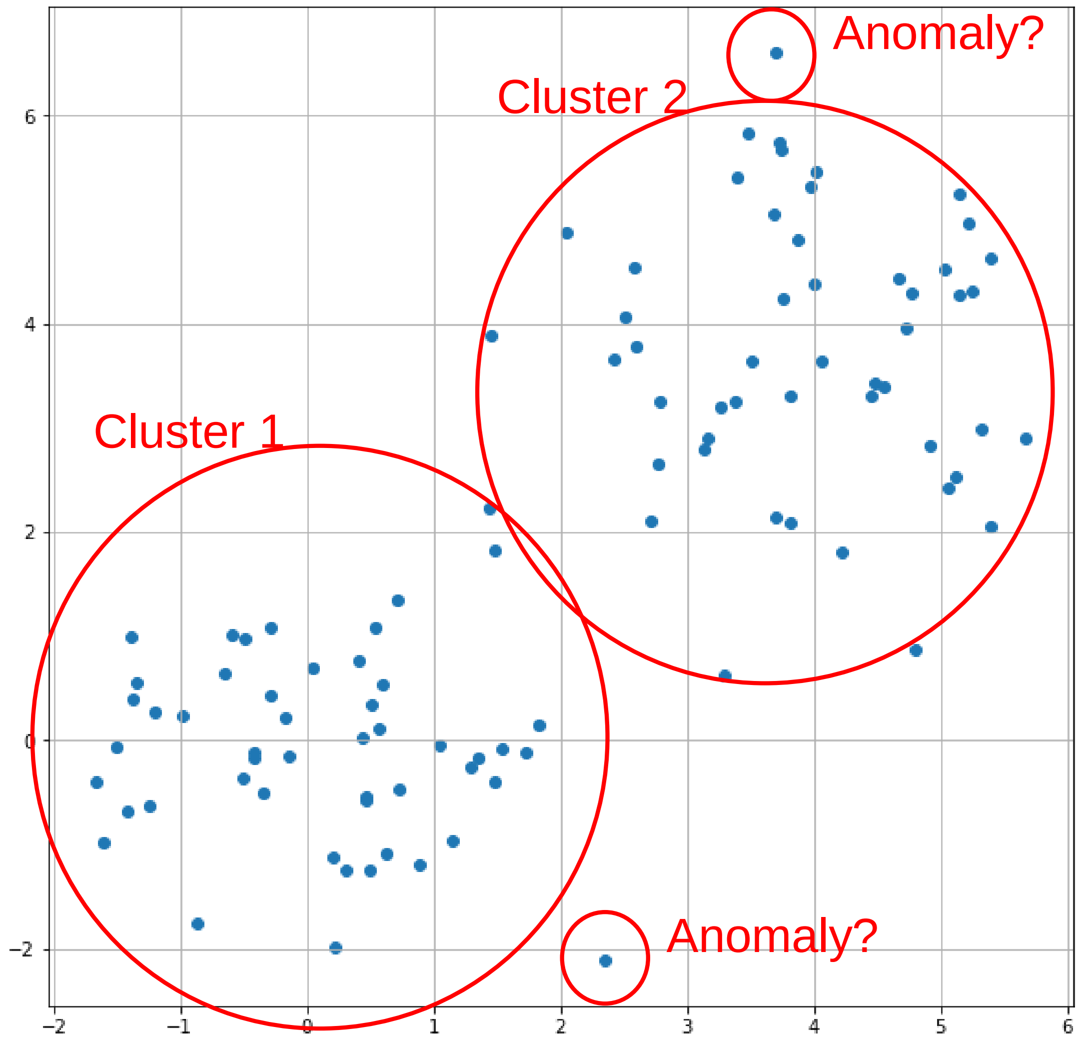


# Solution Design

- **Solution architecture**
  - Data set with no attacks provided
  - Limited data with attacks provided
  - Because very little attack information was provided:
    - Use an unsupervised training method to detect data anomalies that indicate a cyber attack
- **Two unsupervised approaches investigated**
  - Clustering
  - Neural network  autoencoder

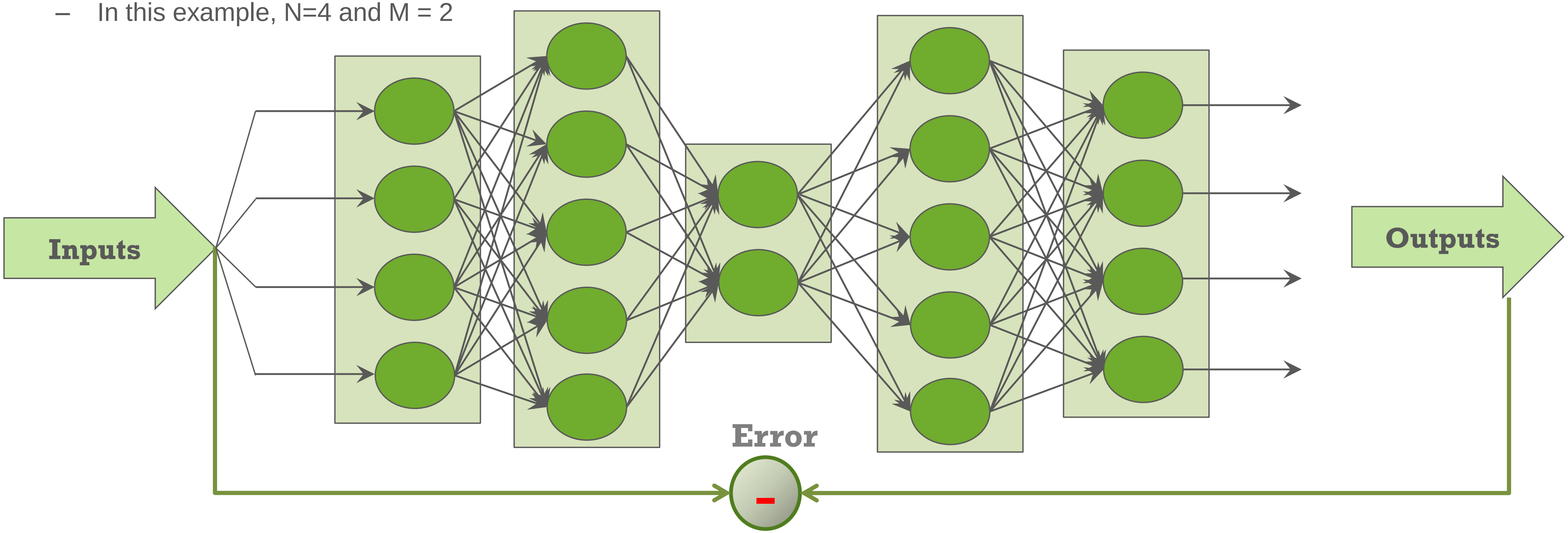
# Unsupervised Learning Approaches

- Useful for unlabeled data sets
- Common approaches include:
  - Clustering
  - Anomaly detection
  - Neural network autoencoders
- Capable of detecting anomalies



# Neural Network Autoencoder

- The desired output is the same as the actual input
- The network is trained to produce this output
- The compression layer in the center reduces the dimensionality from N input nodes to M center nodes
  - In this example, N=4 and M = 2



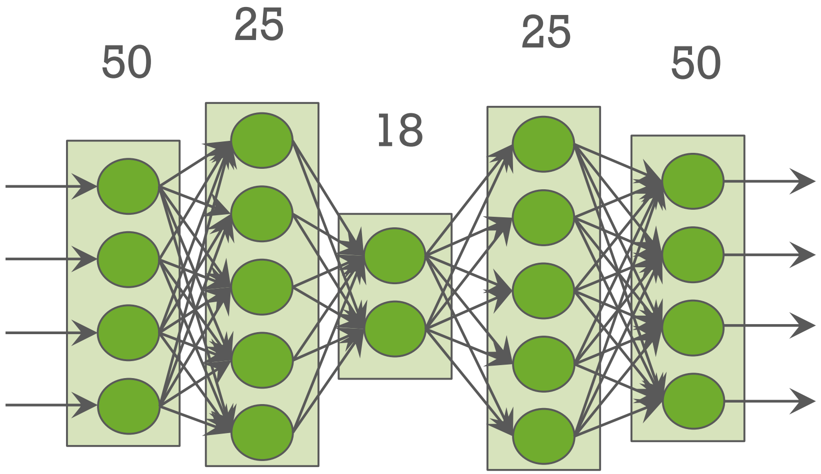

Anomalous data will produce high errors so the autoencoder can be used as an outlier detector

# Solution Design (cont'd)

- **Conducted some experiments with clustering**
  - Was not on track to provide a good solution
- **Experimented with an autoencoder and this promised significant improvement**
- **Continued refinement of architecture throughout development**
  - Number of layers
  - Minimum number of nodes in a layer

# Implementation

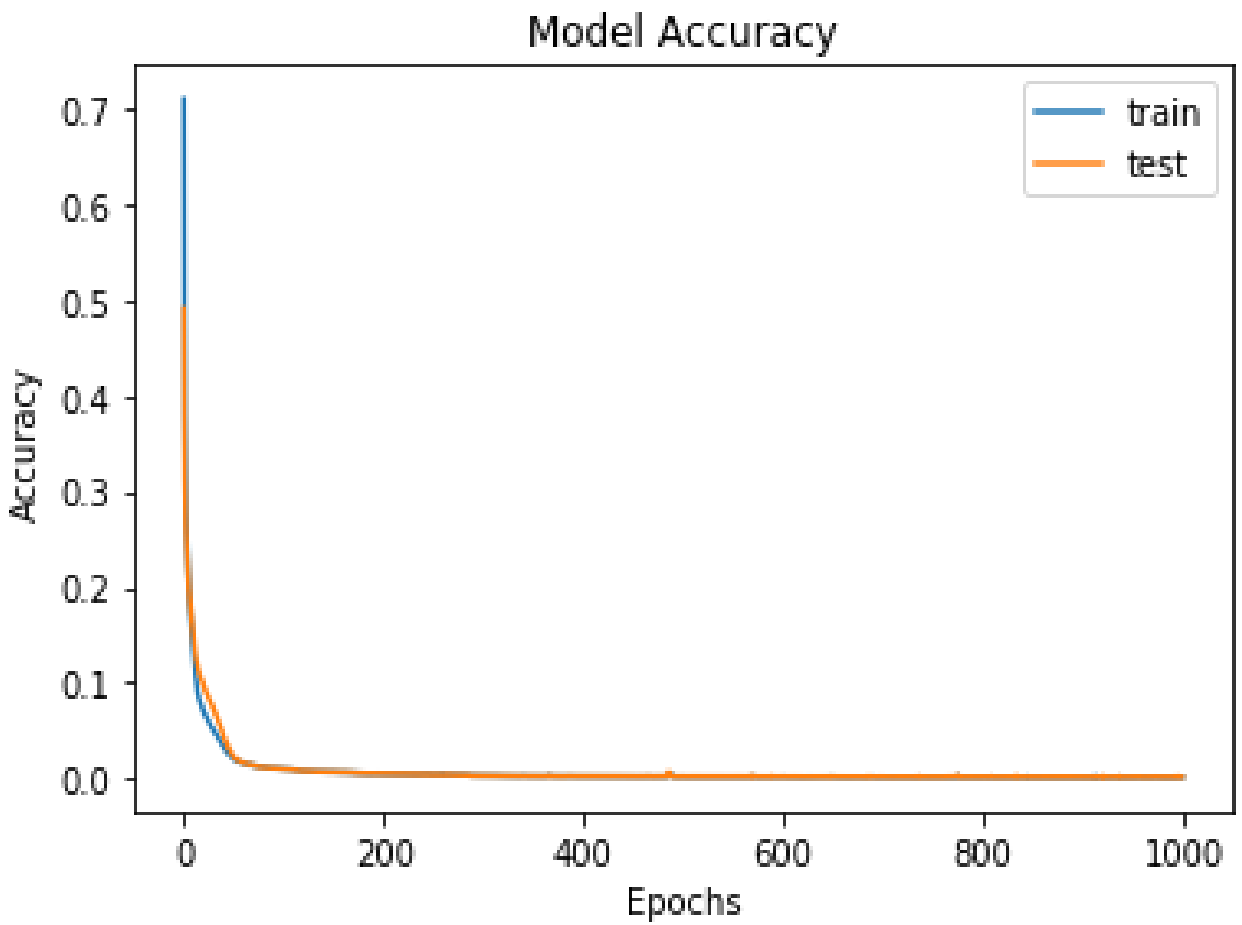
- **Used a neural network autoencoder with:**
  - 50 input nodes
  - 1 for each feature
  - An intermediate layer with 25 nodes
  - An encoding layer with 18 nodes
  - This is the compression factor
  - An intermediate layer with 25 nodes
  - A result layer with 50 nodes
  - The activation function only outputs positive values
  - An output layer with 50 nodes
  - This allows the output to handle both positive and negative values




- **Split the data into a training set with 5,869 samples and a testing set with 2,891 samples**
- **Trained the network for 1,000 epochs (complete passes through the data)**

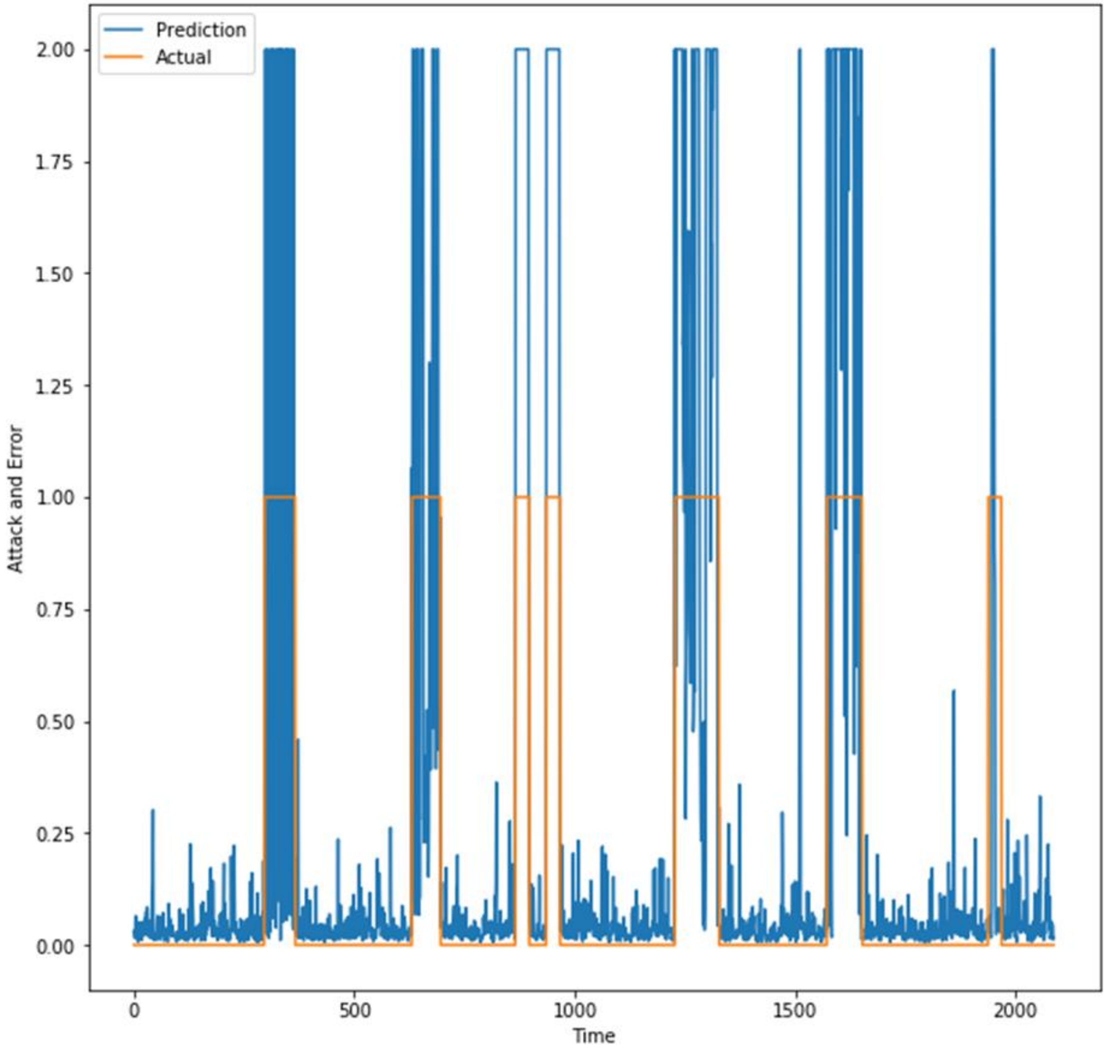
# Implementation

- **Trained model**
- **Reduced mean squared error to more than 99.8%**
- **Completed on a business-class laptop in less than 2 minutes**



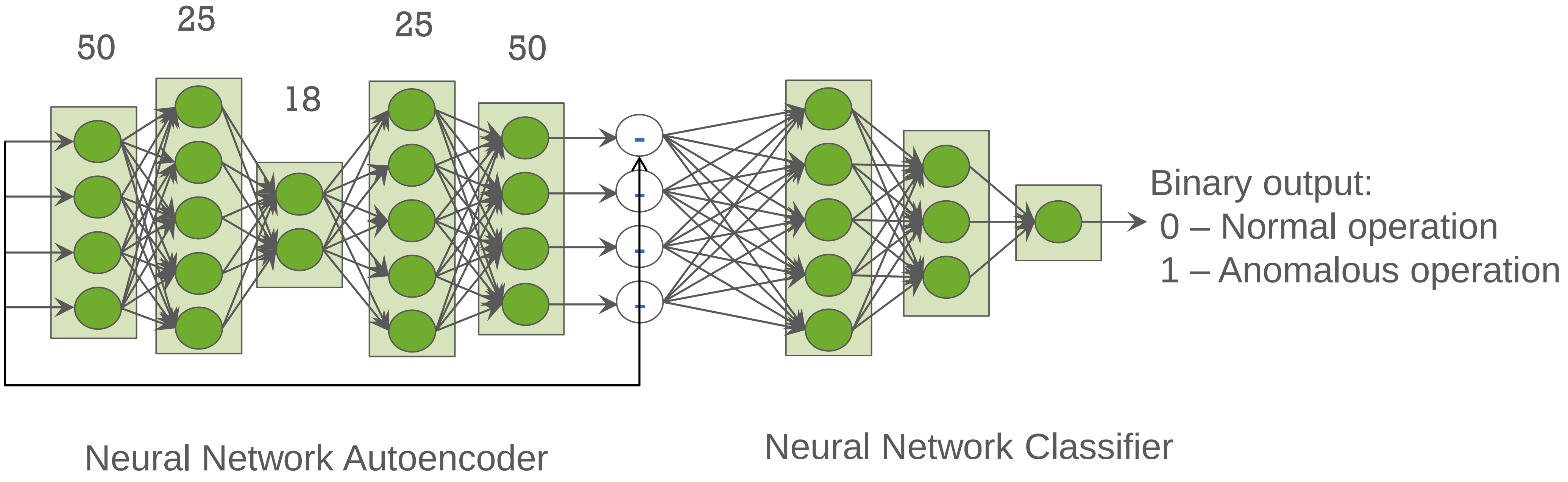
# Initial Results

- **Blue line indicates the magnitude of the error between the input and output of the autoencoder**
- **Orange line indicates the actual attacks**
- **Generally good detection of the hacks**
  - 1 false positive
- **Areas for improvement**
  - Data preprocessing
  - Addition of neural network post-processing layer



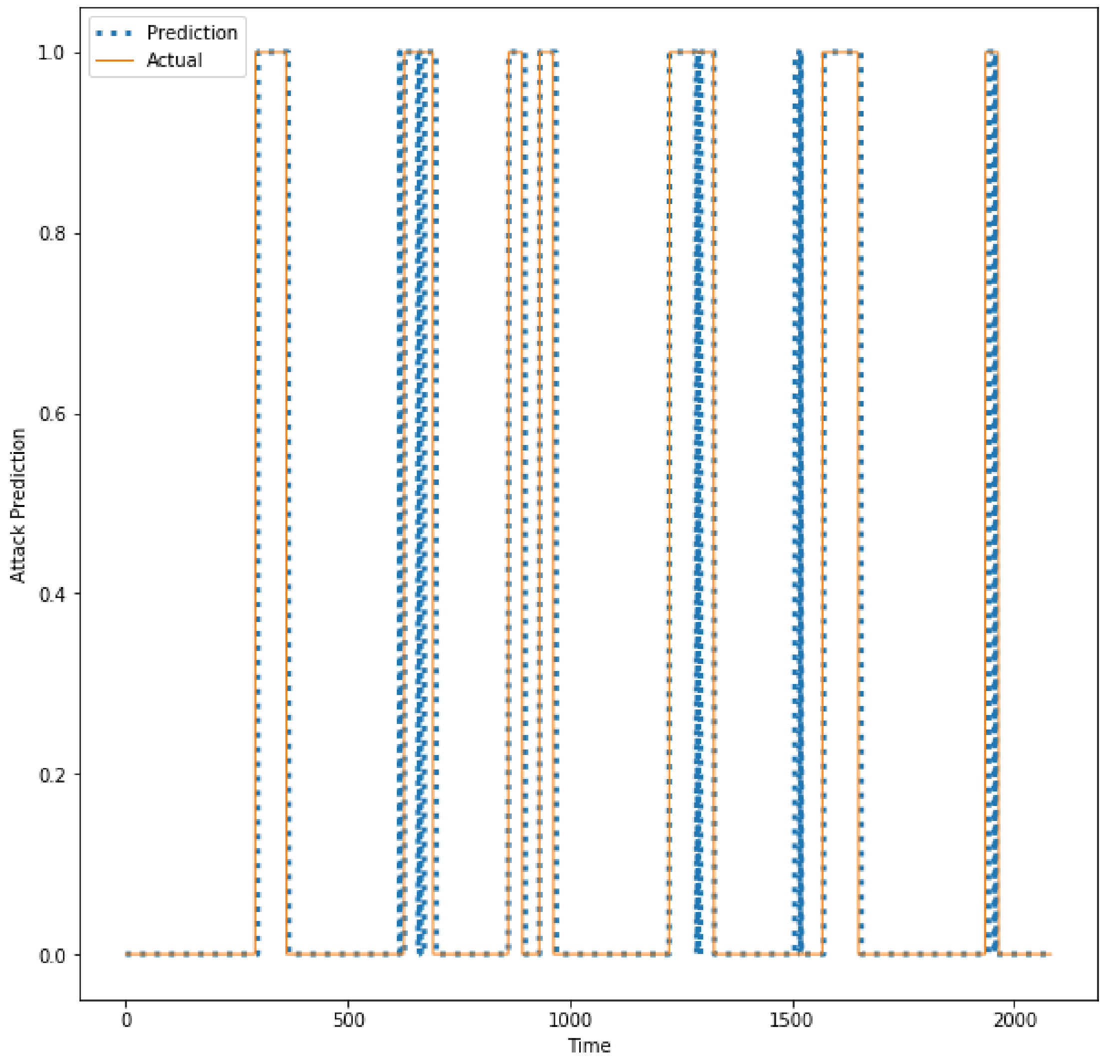
# Neural Network Post Processing

- **Implemented a two layer neural network that post-processed the autoencoder error**
  - Output - Input
- **Both a binary classified and a regression model were tested**
  - Binary classifier performed better



# Results (cont'd)

- **One false positive remains**
- **System able to reliably detect cyberattacks**
- **Areas for improvement remain:**
  - Localize the components impacted by the intrusion
  - Improve handling of infrequent events



# Conclusion

- **Autoencoder approach able to successfully detect performance anomalies in an industrial control system**

- **Results achieved despite relatively small data set**

- **Improvements to approach planned:**
  - Better rejection of false positives
  - Identification of specific equipment being targeted

# Questions

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