INL/CON-24-78337-Revision-0

Leveraging Hydropower Multi-Sensor Data for Inference and Age-Informed Modeling

May 2024

Changing the World's Energy Future

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Idaho National Laboratory

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Motivation

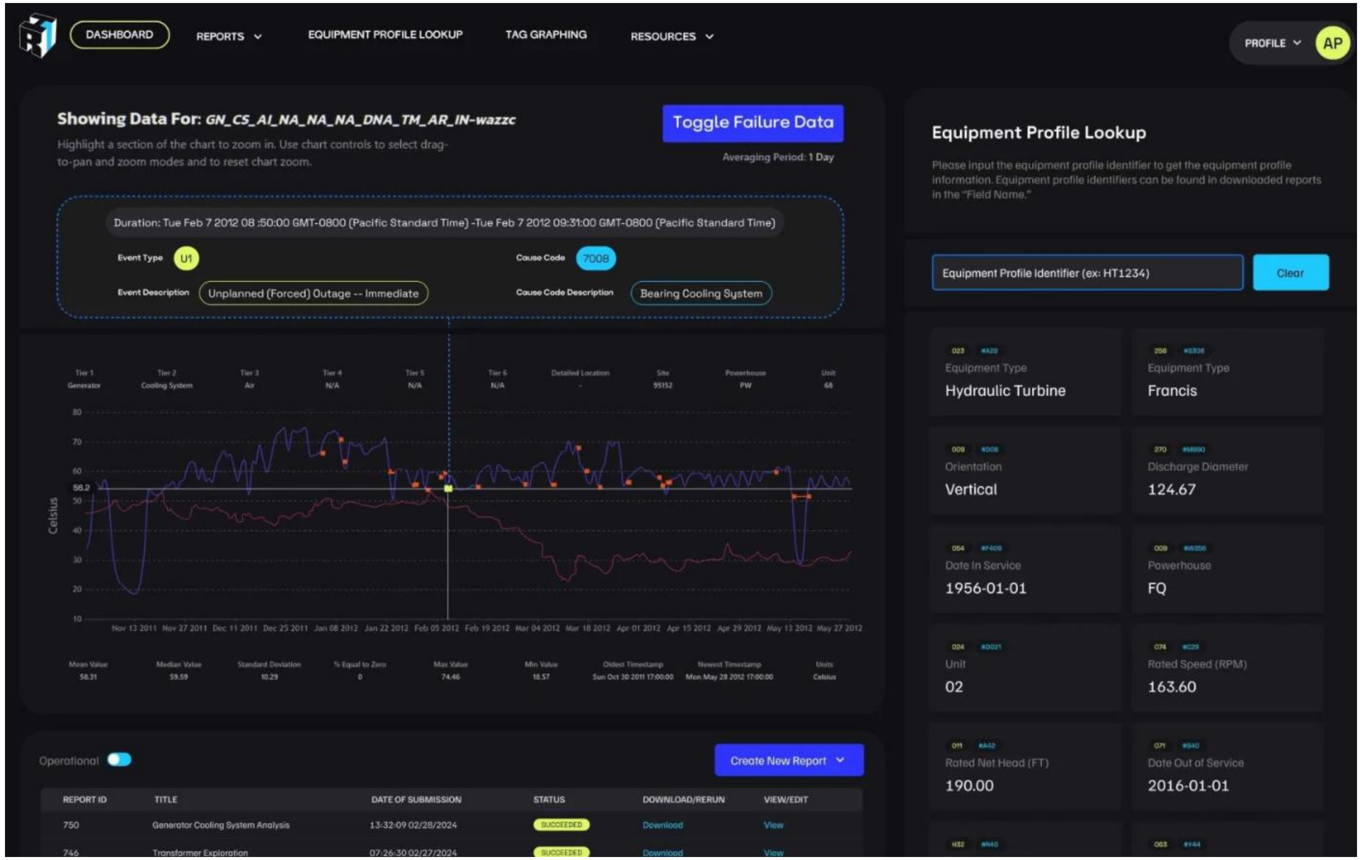
- Increased demand of operational flexibility is putting hydropower assets in unprecedented stress.
- Risks of forced outage and unscheduled maintenance is getting higher.
- Not all hydropower plants are exhaustively equipped with sensors and/or measurement streams for their respective components.
- How to detect, identify, and locate the cause of any event from the unobservable?

Queries being Sought

- What does correlation among multiple datasets infer? How does it change along the pre-event, during event and post-event? How does it vary from normal operating conditions?
  - Can we identify the “cause” time series by observing low/negative correlation?
  - Can we identify set of exogeneous time series by observing high correlation? (These can be later used for inference and/or prediction)
- For a given hydropower component, how does the reaction/response time change along the pre-event, during event, and post-event? How does it vary from normal operating conditions?
  - How does the reaction/response time change in the long run? (This will help to make hydropower dynamic model age-informed).
- How do the reaction/response times of multiple phenomena correlate?
- What will the sensor measurement noise model look like?

Leveraged HRI Database for Data Analytics

- Hydropower Research Institute (HRI): https://hridata.org/
- Anonymized multi-sensor data from 231 plants (955 generators totaling 53GW).
- Analysis carried out
  - Cross-correlation
  - Time constant estimation
  - Clustering
  - Short-term prediction



Focused on Bearings and Generator Windings

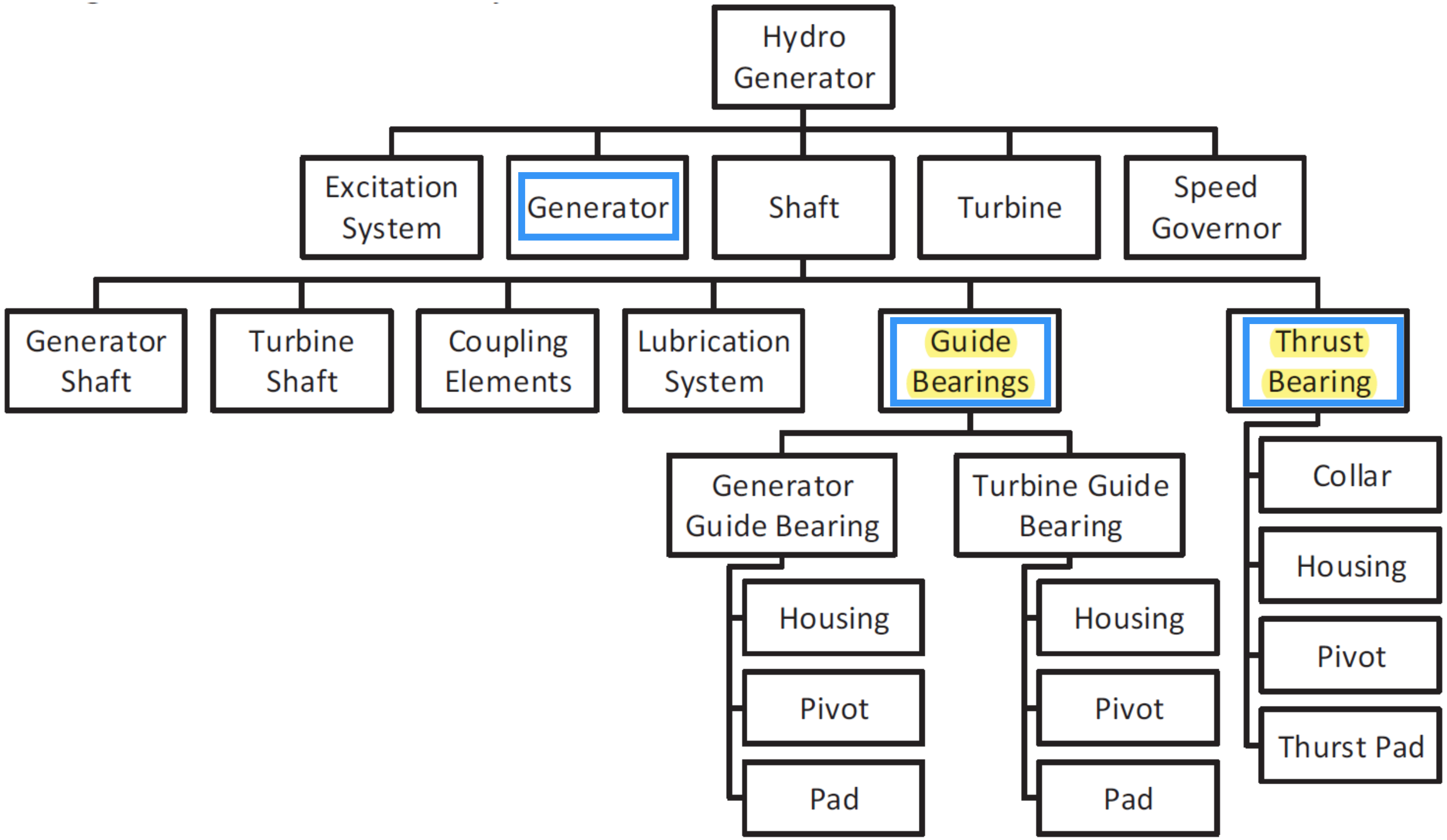
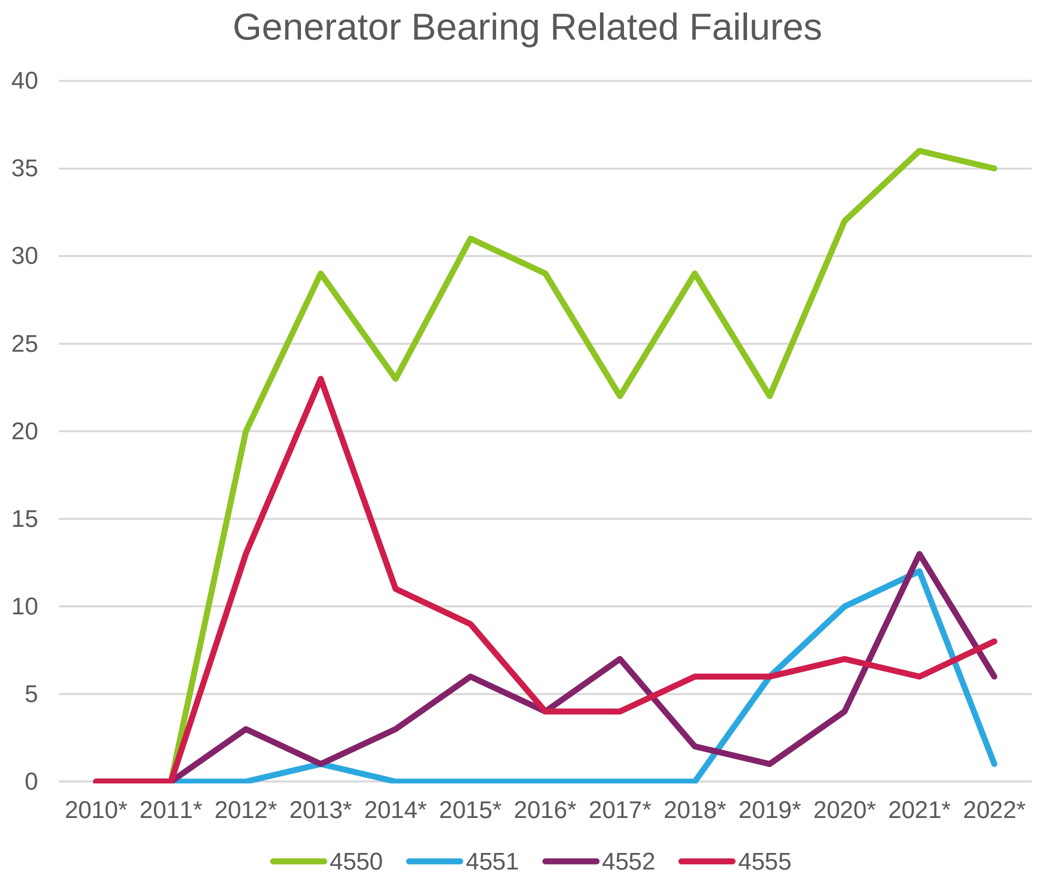


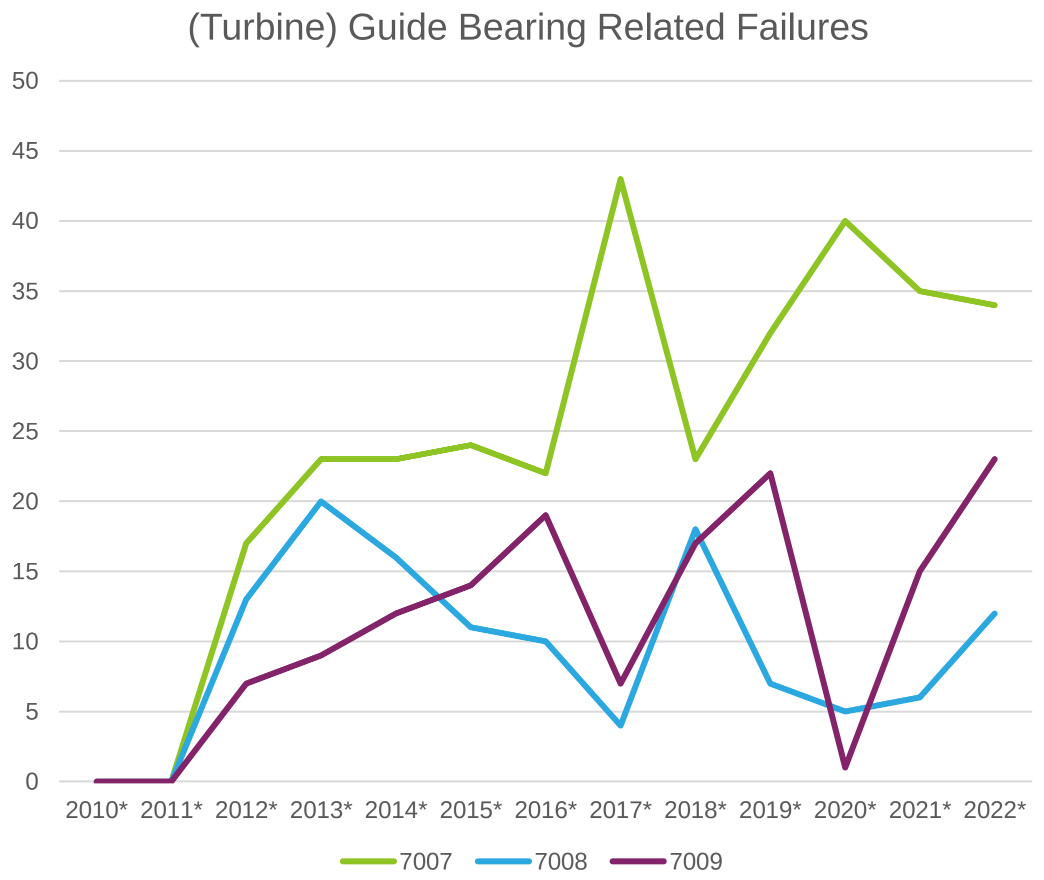
Image Source: Melani et al., "Updating a Hydro Power Plant Monitoring System Through Failure Modes and Symptoms Analysis", 2019

Bearing System Failure Cause Codes

- According to the North American Electrical Reliability Corporation (NERC) classification system (GADS), **seven cause codes** relate directly to hydroelectric bearing system failures:
  - Generator
    - 4550 Generator bearings and lube oil system (including thrust bearings on hydro units)
    - 4551 Generator bearings
    - 4552 Generator lube oil system
    - 4555 Bearing cooling system
  - Turbine
    - 7007 Bearings
    - 7008 Bearing cooling system
    - 7009 Bearing oil system
- Sensor data from various plants for a U1 type failure event (immediate unplanned outage) for each cause code of were analyzed to determine the correlation between different sensors.

Annual Failure Rates by Cause Code





4550 Generator bearings and lube oil system (including thrust bearings on hydro units)
4551 Generator bearings
4552 Generator lube oil system
4555 Bearing cooling system

7007 Bearings
7008 Bearing cooling system
7009 Bearing oil system

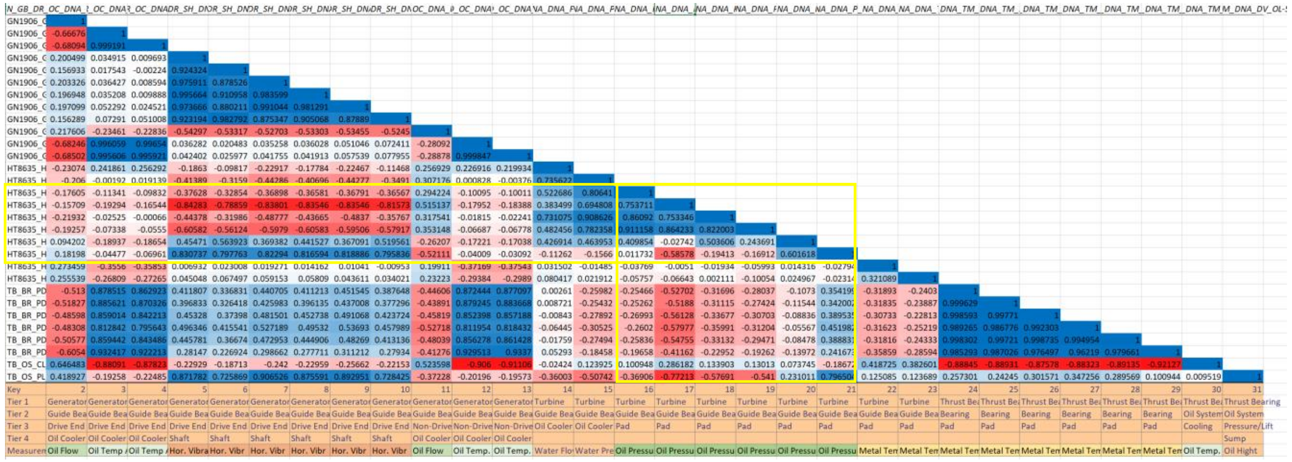
Correlation Analysis on Bearing Sensor Data

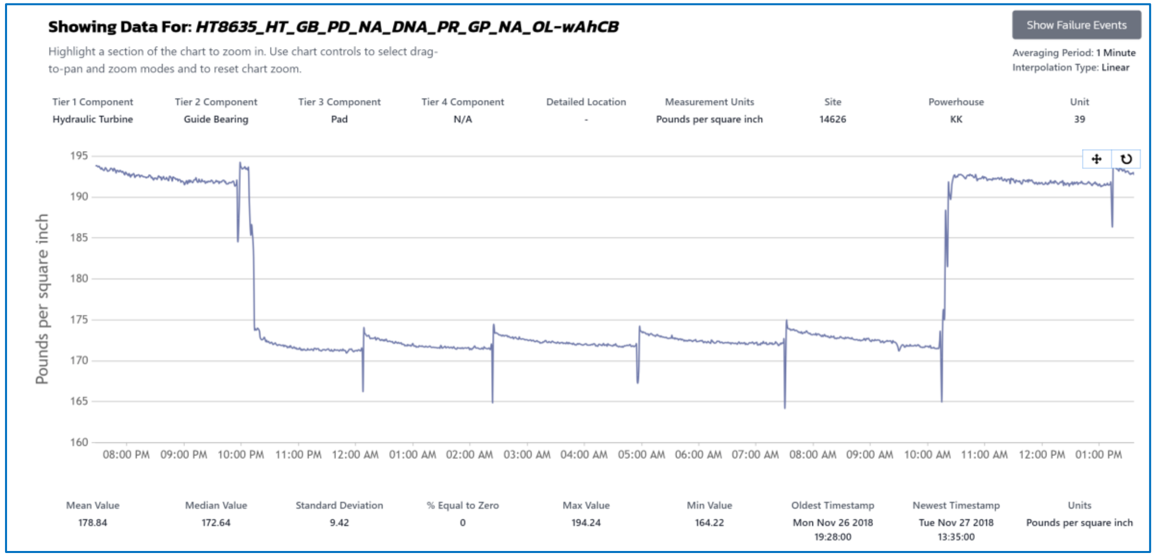
N_GB_DR_	OC_DNA_	_OC_DNA	_OC_DNA	DR_SH_DN	DR_SH_DN	DR_SH_DN	R_SH_DN	R_SH_DN	DR_SH_DN	OC_DNA_	_OC_DNA	_OC_DNA	NA_DNA_F	VA_DNA_P	NA_DNA_	NA_DNA_	NA_DNA_	NA_DNA_	NA_DNA_	NA_DNA_P	_NA_DNA	NA_DNA_	DNA_TM_	DNA_TM_	DNA_TM_	DNA_TM_	DNA_TM_	DNA_TM_	DNA_TM_	M_DNA_D
GN1906_G	1																													
GN1906_G	0.585734	1																												
GN1906_G	0.598091	0.997267	1																											
GN1906_G	0.337914	0.723106	0.679586	1																										
GN1906_G	0.348614	0.756973	0.72158	0.962272	1																									
GN1906_G	0.344495	0.778089	0.737471	0.987361	0.947387	1																								
GN1906_G	0.334162	0.710298	0.666664	0.998141	0.960281	0.987225	1																							
GN1906_G	0.275964	0.503661	0.4521	0.931339	0.831492	0.908556	0.941273	1																						
GN1906_G	0.313258	0.699625	0.650811	0.965257	0.905049	0.947627	0.957703	0.899584	1																					
GN1906_G	-0.13991	0.216171	0.202928	0.265987	0.280943	0.261867	0.265304	0.242623	0.234854	1																				
GN1906_G	0.603835	0.998662	0.998146	0.707197	0.742768	0.761339	0.694768	0.49022	0.682539	0.221886	1																			
GN1906_G	0.589616	0.999571	0.996701	0.725711	0.758326	0.779572	0.713099	0.509657	0.702663	0.225414	0.999315	1																		
HT8635_H	-0.24191	-0.70142	-0.6712	-0.7286	-0.69962	-0.76227	-0.71784	-0.59421	-0.73531	-0.17488	-0.68223	-0.69842	1																	
HT8635_H	-0.19499	-0.48958	-0.47042	-0.49129	-0.46904	-0.5157	-0.48509	-0.40032	-0.49421	-0.12545	-0.47769	-0.48737	0.856568	1																
HT8635_H	0.047977	0.12997	0.124693	0.168922	0.180159	0.165849	0.167054	0.150603	0.149657	0.053365	0.127519	0.130778	0.378049	0.611562	1															
HT8635_H	-0.31253	-0.68361	-0.65326	-0.78084	-0.77085	-0.79387	-0.77637	-0.67107	-0.76236	-0.19537	-0.66943	-0.68317	0.947392	0.837551	0.425028	1														
HT8635_H	0.13396	0.383284	0.3601	0.578731	0.600002	0.557679	0.577757	0.525358	0.531391	0.184159	0.374365	0.38524	0.020989	0.294294	0.852596	0.003509	1													
HT8635_H	0.122297	0.427236	0.410138	0.45548	0.465585	0.465636	0.445896	0.361065	0.440715	0.168448	0.417694	0.427603	0.036256	0.330607	0.886143	0.094686	0.925428	1												
HT8635_H	-0.38051	-0.829	-0.79819	-0.86725	-0.8462	-0.89158	-0.85778	-0.72662	-0.861	-0.2271	-0.8141	-0.8284	0.941133	0.775815	0.205654	0.950899	-0.19737	-0.15273	1											
HT8635_H	0.135452	0.473586	0.450676	0.539523	0.556047	0.552687	0.531178	0.439824	0.513794	0.180582	0.459566	0.47274	-0.0636	0.245015	0.853014	-0.01312	0.918923	0.968949	-0.24387	1										
HT8635_H	-0.29459	-0.82913	-0.81736	-0.69701	-0.73027	-0.73919	-0.68058	-0.48556	-0.66294	-0.25877	-0.81785	-0.82728	0.678858	0.458888	-0.14779	0.636757	-0.41244	-0.45427	0.760022	-0.50907	1									
HT8635_H	-0.29021	-0.8391	-0.82646	-0.70885	-0.73664	-0.7598	-0.69664	-0.50752	-0.67432	-0.25245	-0.82776	-0.83741	0.696638	0.464608	-0.14626	0.645723	-0.41255	-0.45537	0.767404	-0.51258	0.821343	1								
TB_BR_PD	0.43622	0.938629	0.912527	0.87377	0.869701	0.914084	0.860053	0.690633	0.867212	0.25347	0.925205	0.938147	-0.8071	-0.5505	0.147477	-0.77837	0.469396	0.490924	-0.91702	0.5613	-0.85609	-0.86825	1							
TB_BR_PD	0.439461	0.940416	0.914632	0.873082	0.8703	0.913144	0.859276	0.688784	0.866204	0.254118	0.92724	0.939998	-0.80555	-0.54944	0.147828	-0.77788	0.470035	0.490791	-0.91643	0.560819	-0.85613	-0.86836	0.999953	1						
TB_BR_PD	0.435174	0.935319	0.908594	0.883313	0.87788	0.922185	0.87025	0.704266	0.874469	0.25549	0.921834	0.934978	-0.80701	-0.54997	0.149624	-0.78191	0.476986	0.492188	-0.91911	0.563207	-0.85353	-0.86653	0.999748	0.99971	1					
TB_BR_PD	0.415875	0.927695	0.899949	0.886288	0.881831	0.924839	0.873135	0.706214	0.876865	0.256538	0.913142	0.927079	-0.8108	-0.55156	0.150627	-0.7841	0.480813	0.495179	-0.91969	0.568409	-0.85519	-0.86832	0.999272	0.999127	0.999601	1				
TB_BR_PD	0.430503	0.935259	0.908498	0.879337	0.875882	0.918772	0.866039	0.698213	0.871662	0.255896	0.921567	0.934811	-0.80797	-0.55064	0.149188	-0.78109	0.474597	0.492319	-0.91831	0.564047	-0.85572	-0.86826	0.999851	0.999776	0.999826	0.999612	1			
TB_BR_PD	0.439526	0.950601	0.92779	0.843585	0.850371	0.887061	0.827937	0.641793	0.839623	0.248656	0.937934	0.949737	-0.79957	-0.54576	0.143652	-0.76469	0.453541	0.488077	-0.90611	0.554857	-0.863	-0.87418	0.997597	0.997871	0.996251	0.9955	0.996794	1		
TB_OS_CL	-0.44785	-0.86336	-0.82824	-0.89722	-0.8397	-0.92188	-0.88626	-0.79553	-0.9198	-0.28126	-0.85389	-0.86761	0.776338	0.529838	-0.13765	0.763796	-0.45845	-0.45833	0.897839	-0.51972	0.768915	0.781874	-0.9551	-0.95452	-0.95699	-0.95418	-0.95567	-0.94025	1	
TB_OS_PL	0.354713	0.8168	0.774886	0.955108	0.907256	0.976792	0.947305	0.853069	0.947398	0.266094	0.798767	0.818048	-0.80263	-0.54281	0.155613	-0.79603	0.518964	0.485538	-0.91224	0.568043	-0.78094	-0.7978	0.957227	0.956038	0.9618	0.964366	0.960125	0.937126	-0.96405	1
Key	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Tier 1	Generator	Generator	Generator	Generator	Generator	Generator	Generator	Generator	Generator	Generator	Generator	Generator	Turbine	Turbine	Turbine	Turbine	Turbine	Turbine	Turbine	Turbine	Turbine	Turbine	Thrust Bea	Thrust Bea	Thrust Bea	Thrust Bea	Thrust Bea	Thrust Bea	Thrust Bea	Thrust Bea
Tier 2	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Guide Bea	Bearing	Bearing	Bearing	Bearing	Bearing	Bearing	Oil System	Oil System
Tier 3	Drive End	Drive End	Drive End	Drive End	Drive End	Drive End	Drive End	Drive End	Drive End	Non-Drive	Non-Drive	Non-Drive	Oil Cooler	Oil Cooler	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Pad	Cooling	Pressure/L
Tier 4	Oil Cooler	Oil Cooler	Oil Cooler	Shaft	Shaft	Shaft	Shaft	Shaft	Shaft	Oil Cooler	Oil Cooler	Oil Cooler																		Sump
Measuren	Oil Flow	Oil Temp /	Oil Temp /	Hor. Vibra	Hor. Vibr	Hor. Vibr	Hor. Vibr	Hor. Vibr	Hor. Vibr	Oil Flow	Oil Temp.	Oil Temp.	Water Flo	Water Pre	Oil Pressu	Oil Pressu	Oil Pressu	Oil Pressu	Oil Pressu	Oil Pressu	Metal Ten	Metal Ten	Metal Ten	Metal Ten	Metal Ten	Metal Ten	Metal Ten	Metal Ten	Oil Temp.	Oil Hight

Correlation matrix of 30 bearing system sensors across unit KK-39.

KK-39 7009

- Abnormality in turbine oil pressure. Most sensors show pressure rise during event, but one shows a notable drop.
- Likely indicative of the type of repairs made.





Findings on Bearing Sensor Data Analysis

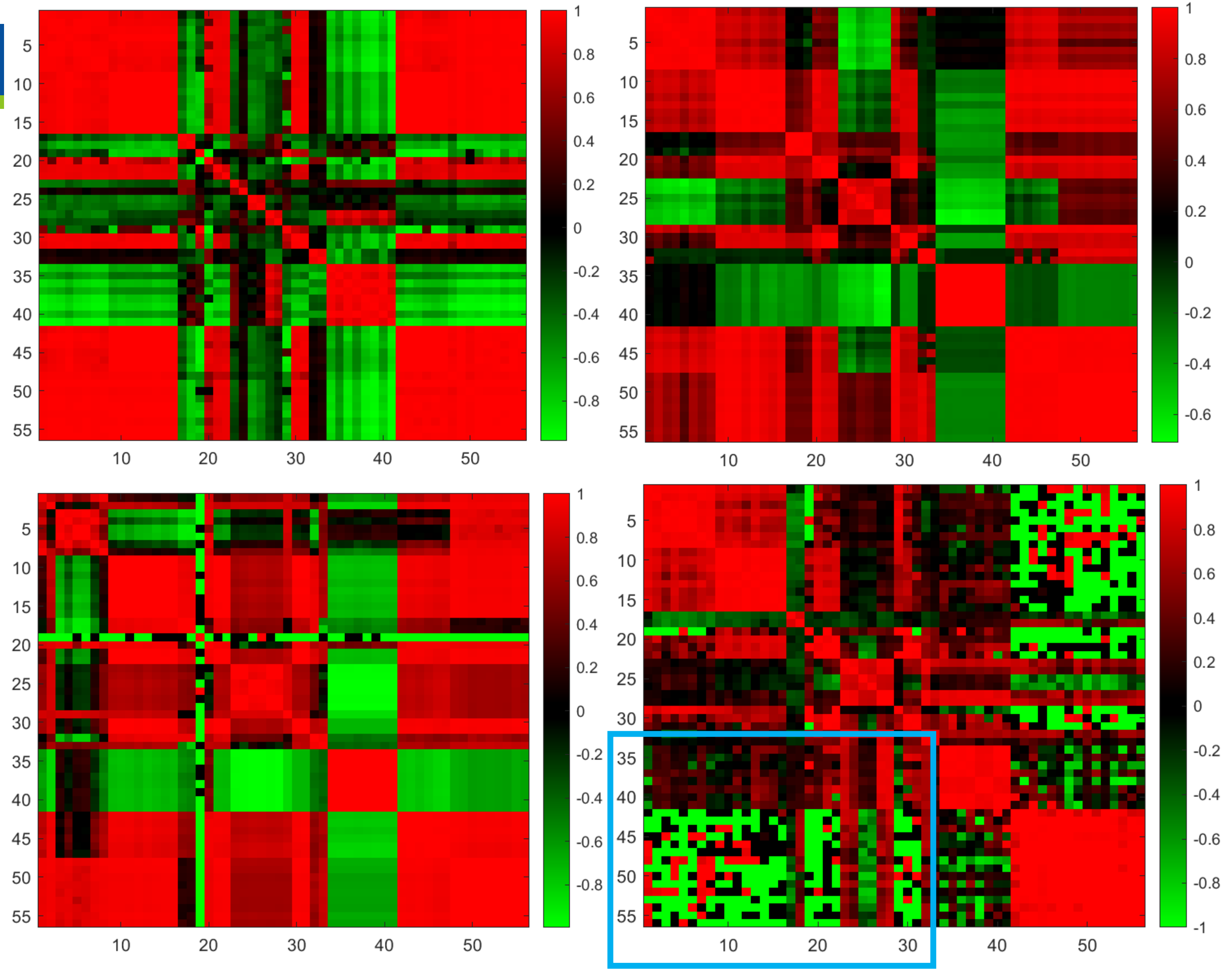
- **Similar sensors** (e.g., All six thrust bearing pad temp. sensors on KK-39) have a **high correlation**.
  - If one sensor had a different correlation from the others, it is likely that bearing pad is the cause of the failure.
  - Thermal cycling due to failure event.
- Magnitude of shaft **vibration** generally has a **low correlation with other variables**.
- The **thrust bearing and generator bearings** measurements tend to have a **strong correlation**.
- Thrust bearing **oil cooler** has a strong **negative correlation** with thrust bearing and generator **bearing temp**.
  - Makes sense because often both bearing systems are fed and cooled by the same oil system.
- Turbine guide bearings run at a much lower temperature, which may explain why there is a negative correlation to the other bearings.
- During a shutdown event, the oil will continue to absorb excess heat from the bearings.

Correlation Analysis on Rotor Winding Event Records

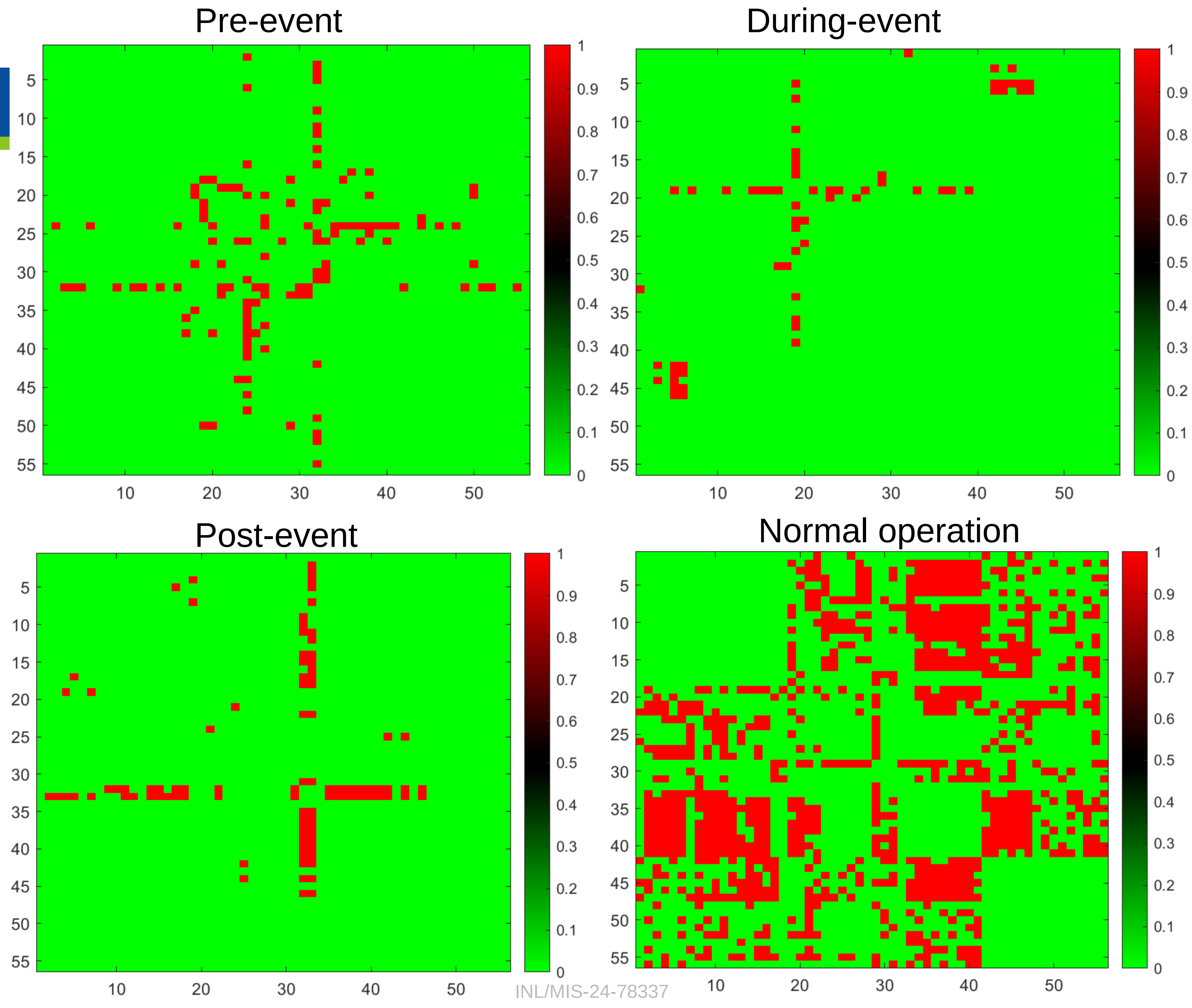
- Investigate correlation of generator measurements before, during and after the following rotor winding events:
  - 07/13/2012 08:49:10-10:44:40
    - Pre-event: 07/13/2012 07:49:10-08:49:10
    - Post-event: 07/13/2012 10:45:00-15:45:00
  - 07/29/2019 15:20:02-07/31/2019 21:19:49
    - Pre-event: 07/29/2019 14:20:02-15:20:02
    - Post-event: 07/29/2019 21:20:00- 07/30/2019 02:20:00
  - 08/16/2019 03:09:30-18:49:11
    - Pre-event: 08/16/2019 02:09:30-03:09:30
    - Post-event: 08/16/201918:50:00-23:50:00
- Investigate correlation during normal operation between 2012 and 2014
  - 2012 Jan, Apr, Jul, Oct
  - 2013 Feb, May, Aug, Nov
  - 2014 Mar, Jun, Sept, Dec

Winding Event Records Analysis

Normal operation scenario has weaker correlations.



1-19: Cooling system air temperature
20-22: Guide Bearing/Drive End Guide/Oil Cooler
23-28: Guide Bearing/Drive End Guide/shaft
29-31: Guide Bearing/Non-Drive End Guide/Oil Cooler
32-33: Rotor field current
34-41: Stator airgap vibration
42-47: Stator core temperature
48-56: Stator winding temperature measurements



T test for correlation coefficient

- Green means statistically important
- Red means not statistically important
- Most of correlation coefficients are statistically significant during pre-/ during-/ post-event scenario
- A lot of correlation coefficients are not significant during normal operation

Findings on Rotor Winding Data Analysis

- Stator measurements have similar correlation coefficient pattern in pre-/ during-/ post-event scenarios, but different in normal operation.
- In pre-/ during-/ post-event scenarios,
  - Cooling system air temperature is positively correlated with stator core temperatures and stator winding temperature
  - Cooling system air temperature is negatively correlated with stator airgap vibration

	Outages	**Normal operation**
Positive correlation	A, B, D, G, H are correlated with each other; H is correlated with A, B, C, D, and E;	F is correlated with A, B, C, D, and E;
Negative correlation	A is correlated with B, D, G, and H; D is correlated with G and H; E is correlated with F; G is correlated with H;	F is correlated with A, B, and D;

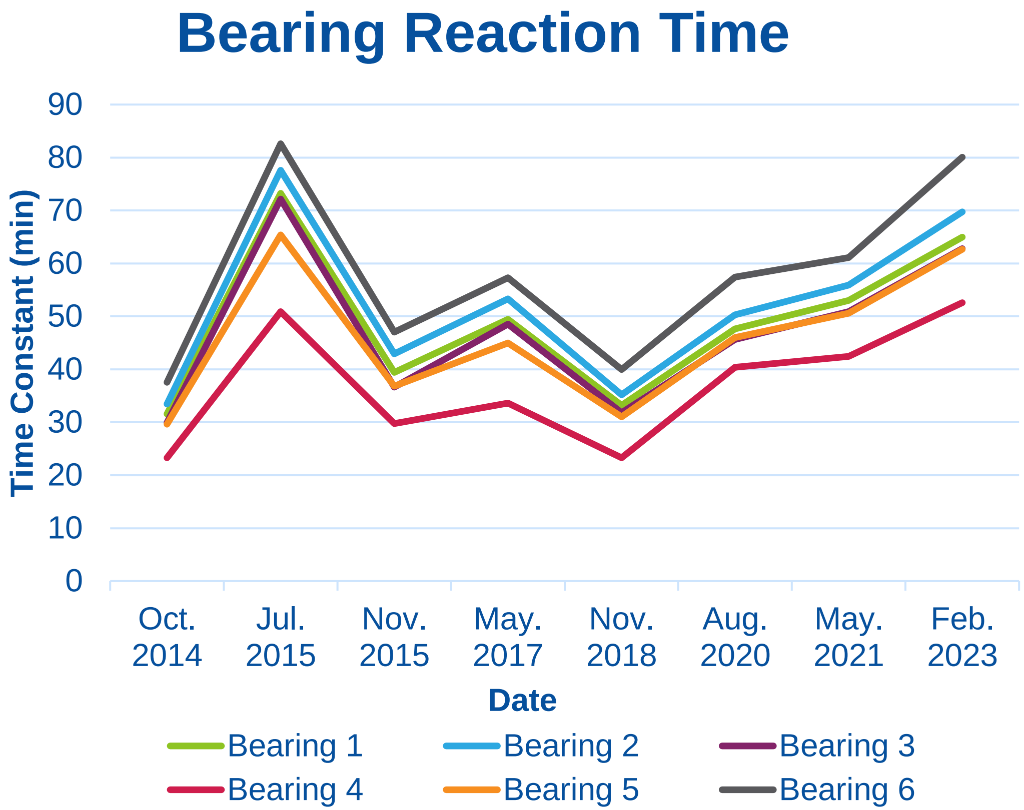
A: Cooling system air temperature measurement 1-19;
B: Guide Bearing/Drive End Guide/Oil Cooler measurement 20-22;
C: Guide Bearing/Drive End Guide/shaft measurement 23-28;
D: Guide Bearing/Non-Drive End Guide/Oil Cooler measurement 29-31;
E: Rotor field current measurement 32-33;
F: Stator airgap vibration measurement 34-41;
G: Stator core temperature measurement 42-47;
H: Stator winding temperature measurement 48-56.

Time Constant Analysis

- Another method of analysis measures the speed of the system response, measured by calculating the time constant.
- We are interested to see if the time constant varies as components age. Therefore, we analyze:
    i. Same sensor across different events.
    ii. Different sensors of the same type for the same event.

Time Constant Analysis on Bearing Sensor Data

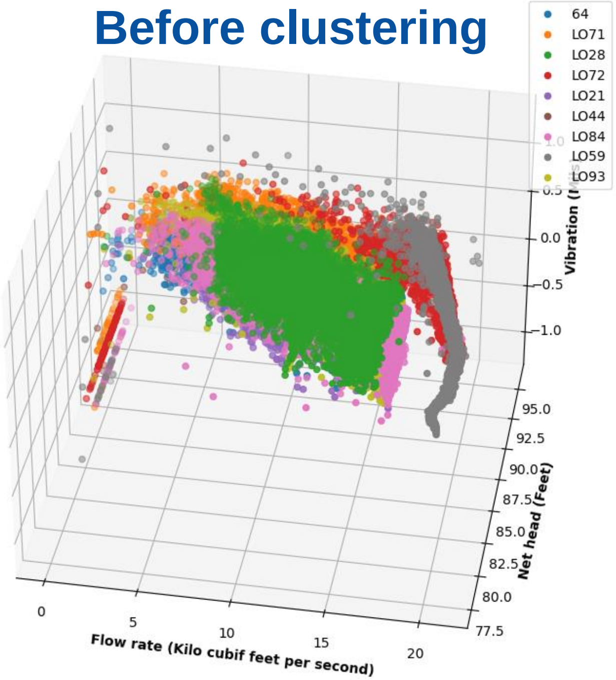
- Demonstrates range of time constants.
- May inform team of which bearing pad is experiencing the most wear due to thermal cycling.
- Consistent location relative to other bearings.
- **Higher variance between bearings may indicate that the component has been damaged.**
- Raises questions regarding the effect of seasonal temperature shifts on the time constant.

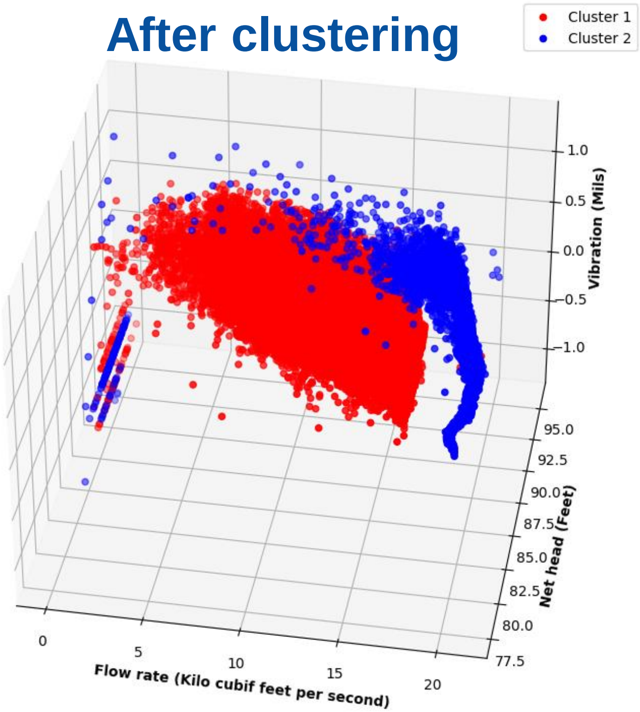


Time constant measured from six temperature sensors within the thrust bearing pad of unit KK-39.

RNN Models based on K-means Clustering Results

- **9 Kaplan Turbines at Site # 36922**
- **Turbines 72 and 59** have larger capacity and higher rated power.
- 1-year time series data of **flow rate, net head, and vibration data.**
- Train Recurrent Neural Network (RNN) models for two clusters, respectively.
- Compared with no cluster, vibration prediction errors of cluster 1 decrease, while those of cluster 2 increase.





	Mean absolute err (mils)	Max absolute err (mils)	Mean relative err	Max relative err	Root mean square err
Cluster 1	1.092	12.792	0.669	33.36	1.503
Cluster 2	2.000	20.964	1.752	47.169	2.324
No cluster	1.175	26.452	0.697	22.118	2.171

1 mil = 1/1000 in.

$$relative\ error = \frac{absolute\ error}{true\ vibration}$$

Summary

- Analysis of multi-sensor anonymized data from HRI can support
  - Root cause identification. (*lubrication valve or bearing?*)
  - Inference (i.e., estimate the unobservable) problem formulation. (*given the temperature, how was the shaft vibration?*)
  - Complementing data lacks for “similar” hydropower units. (*map the log writeups with .csv time series*)
  - Robust short-term prediction of a physical phenomena. (*smart and predictive maintenance*)

Thank you!

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Idaho National Laboratory