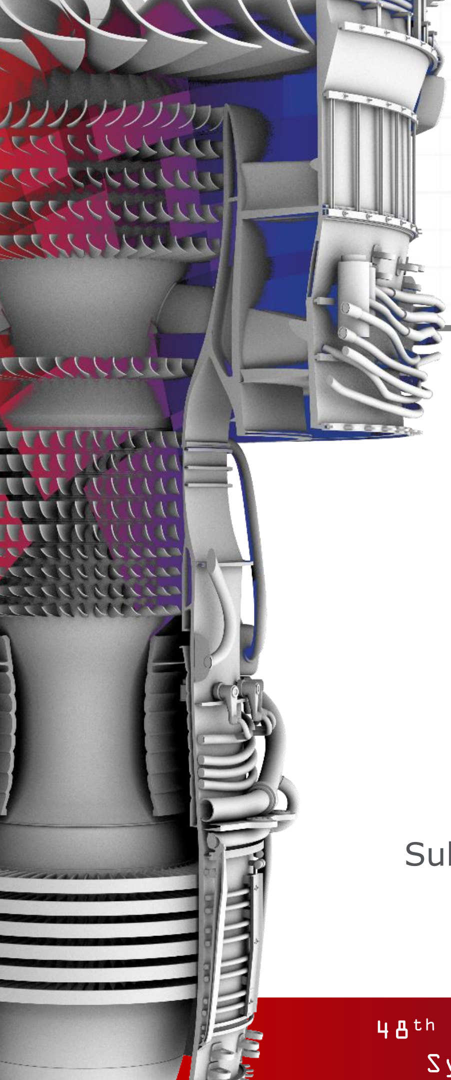

TURBOMACHINERY & PUMP SYMPOSIA

Post-Event Analysis of Subsea Electrical Submersible Pumps Using Electrical Waveform Monitoring (EWM)

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- Shell TA in Flow Assurance and Subsea Boost
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- BS in Nuclear Engineering – Texas A&M Univ
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- Established TAMU Networked and Intelligent Machine Lab
- Granted patents for machine condition assessment and machine learning
- Over 160 journal and conference papers authored / Fellow of the ASME

Agenda

- ❑ Problem Statement and Objectives
- ❑ Electrical Waveform Monitoring
- ❑ Key Lessons Learned
- ❑ Concluding Remarks

Problem Statement

Monitoring the mechanical and electrical health (condition) of subsea ESPs is challenging. ESPs operate in harsh environments and remote subsea locations which makes it difficult to implement and maintain any in-situ monitoring system. For this and other reasons, ESPs have a relatively short life and are typically operated to failure with little to no warning. Shell operates five subsea ESPs in the Gulf of Mexico and sought to implement a topside conditioning monitoring system to reduce work-over cost and limit production losses

Objectives

- Demonstrate top-side installation of non-invasive waveform capture hardware
- Capture, process and archive continuous electrical waveform data
- Demonstrate feasibility of detecting mechanical and/or electrical events

Electrical Waveform Monitoring Description

- ❑ Continuously measures electrical waveforms topside at the switchgear or drive output locations
- ❑ Real-time capture of 3-phase voltage and current readings at high sampling rate

- ❑ Physics-based algorithms generate in real-time torque and impedance related measurements which are used as features (or leading indicators) related to asset mechanical and electrical health

- ❑ Machine learning algorithm predict the longer-term changes in asset health, while filtering out the shorter-term changes caused by operating condition variations

Electrical Waveform Monitoring Description

For mechanical condition tracking, EWM algorithms detect slight changes in torsional signatures caused by change in motor/pump mechanical condition:

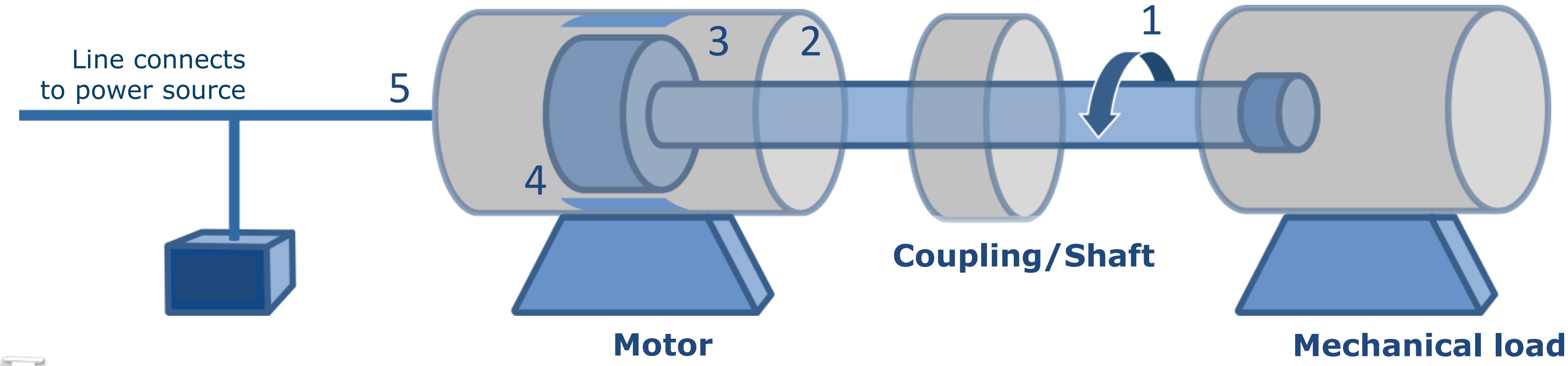
1. Bearing Damaged

2. Shaft Communicates Torsional Energy

3. Motor Rotor Impacted

4. Air Gap Senses Change

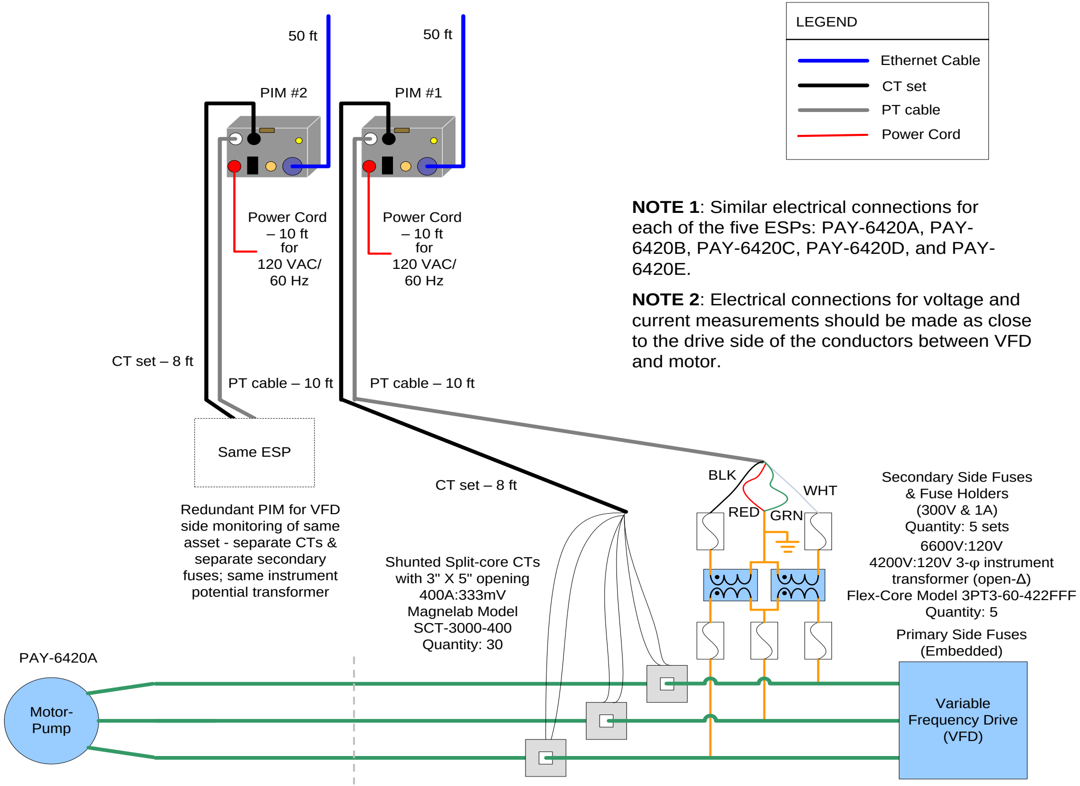
5. Current Reflects Variation



Topside ESP Electrical Connections Diagram

Hardware description

1. A-to-D converter
2. CTs
3. PTs
4. Power Cable



NOTE 1: Similar electrical connections for each of the five ESPs: PAY-6420A, PAY-6420B, PAY-6420C, PAY-6420D, and PAY-6420E.

NOTE 2: Electrical connections for voltage and current measurements should be made as close to the drive side of the conductors between VFD and motor.

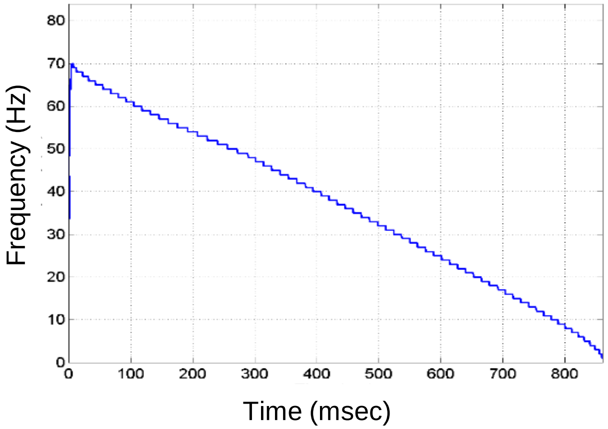
Key field data observations

1. **Post-shutdown reverse rotation**
   - On-set of reverse rotation
   - Tracking of shaft synchronous speed
   - Duration of reverse rotation
   - Overall trend in reverse rotations following shutdowns
2. **Asset mechanical health**
   - Mechanical failures events analyzed
   - Onset of mechanical failures identified in post-event processing
   - Causal relation between shutdown/start-ups and mechanical health
3. **Asset electrical health**
   - Ground faulted detection and tracking
   - GFIC trip on 15-NOV-2017

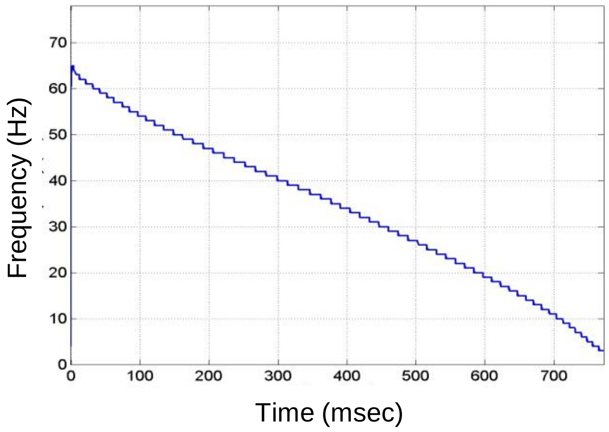
1 Post-shutdown reverse rotation identification

- EWM frequency domain analysis allowed identification of speed and duration of reverse rotation

Reverse rotation event
Duration of 963 sec with max rotation of 72 Hz



Reverse rotation event
Duration of 772 sec with max rotation of 65 Hz



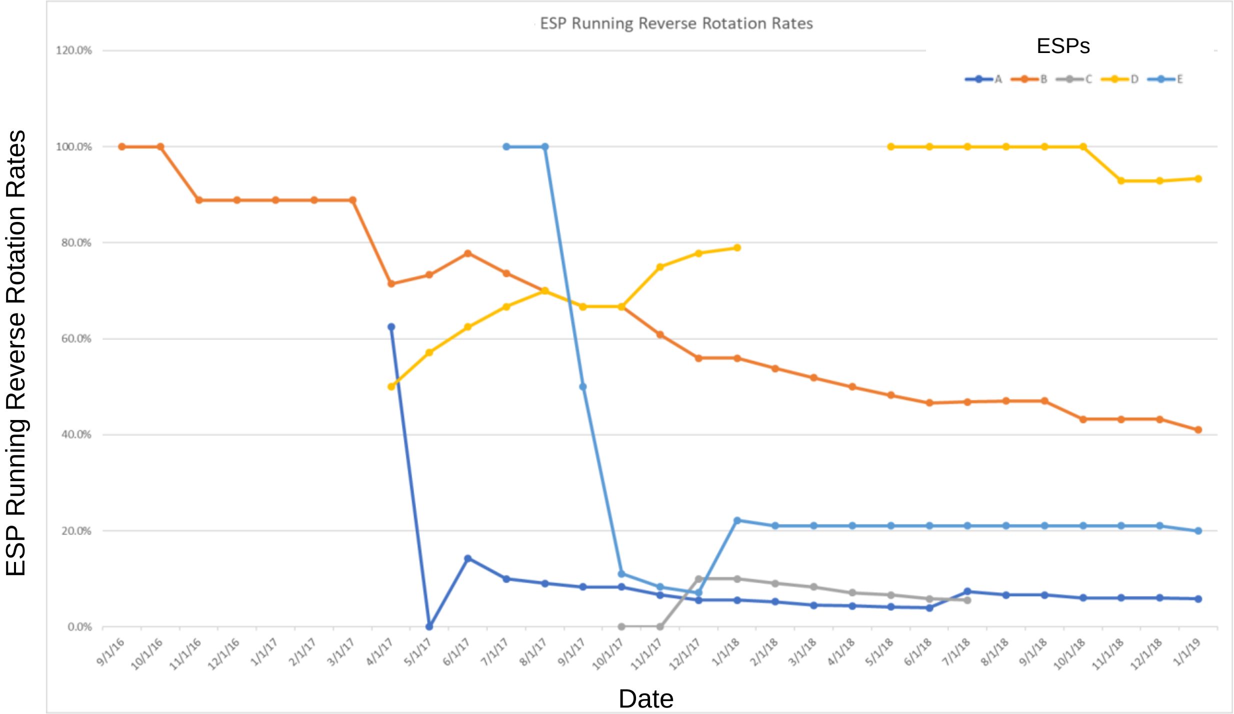
1 Running Rates of Reverse Rotations at Shutdown

- ❑ Total 5 ESPs monitored
- ❑ Total events:

157 shutdowns

59 reverse rotations

All rates managed down, with notable exception of ESP-D



1 Observations on Shutdown/Reverse Rotations

❑ Identification of post-shutdown reverse rotation

- Robust algorithm to detect and track reserve rotation
- Accurately track speed and duration of over 50 reverse rotation events
- Prior EWM, suspected of reverse rotation with no real data. “If we can’t measure it, we cannot manage it!”

❑ Reduction of reverse rotation

- Operation changes led to reduction of number of reverse rotations as a fraction of total shutdowns
  - ESP-A <10%
  - ESP-C <10%
  - ESP-E at 20%
  - ESP-B at 40%
  - ESP-D at 90%

❑ Improvements in ESP reliability

- Largely due to implementation of EWM analysis, operations team was enabled to invest in significant ESP system improvements. Moreover, EWM analysis helped ESP OEM/manufacturer to improve its value proposition

2 Mechanical Health Trend

Three ESP failure events attributed to purely mechanical reasons have been analyzed using EWM

- Two of the events have waveforms that can be interpreted and processed
- One of the events' waveforms are masked by late stage ground-faulted distortions

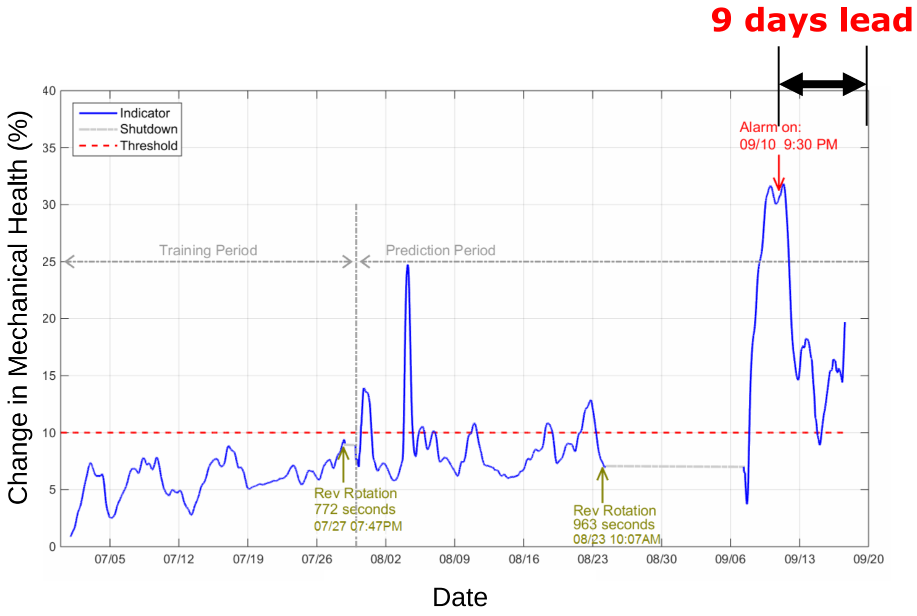
In-Situ Processing	Post-Event Processing
Processing based on:	Processing based on:
• On-premise measurements	• On-premise measurements
• No significant historical ESP data	• ~60 ESP-months of historical data
• 1 failure event	• 2 failure events
• No tuning of algorithms to account for special needs of ESPs	• Tuning of algorithms to account for phenomena such as shorter MTTF of ESPs

2 Waveform Data Processing for Failure Event #1

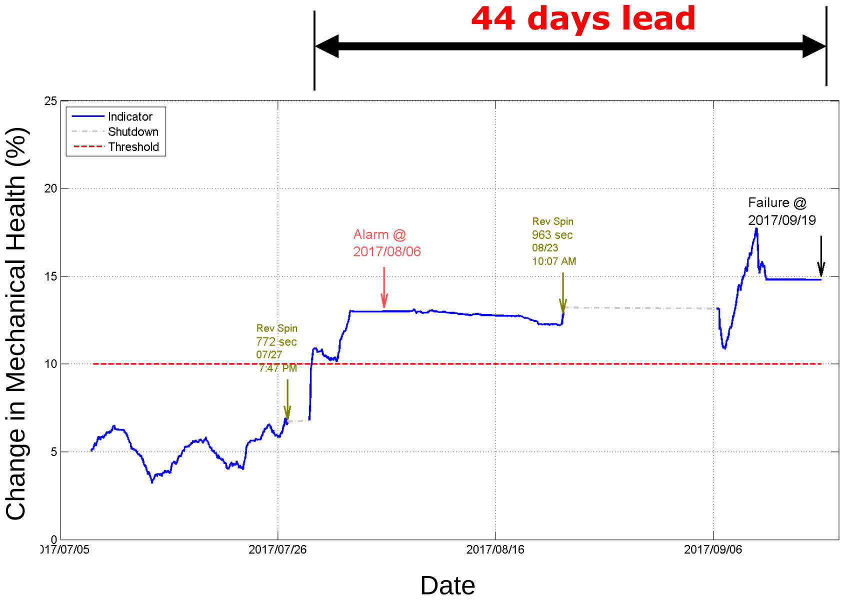
- In-Situ Processing:
  - July 1 through September 19, 2017 – 11 weeks of data
  - Extended shutdown in Aug/Sep 2017 – 2 weeks of no data
  - This leaves about 9 weeks of useful data
    - Learning process requires 4 weeks of data
    - Leaving roughly 5 weeks of data for trending and event detection
- Post-Event Processing:
  - Same data as In-Situ Processing
  - Data available from all other ESP's to learn and test mechanical health trend

2 Failure Onset Prediction for Event #1

In-Situ



Post-Event



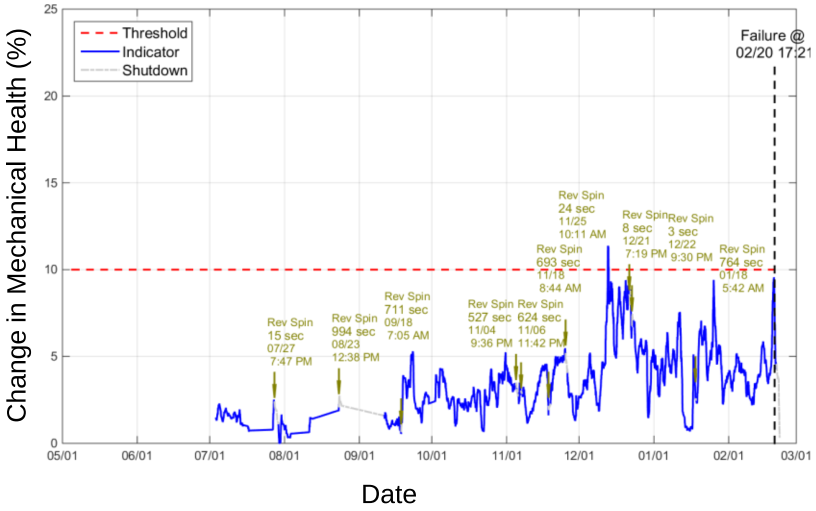
2 Waveform Data Processing for Failure Event #2

- In-Situ Processing:
  - July 1 through February 20, 2018 – 30 weeks of data
  - Extended shutdown in Aug/Sep 2017 – 2 weeks of no data
  - This leaves about 28 weeks of useful data
    - Learning process requires 4-5 weeks of data
    - Leaving roughly 24 weeks of data for trending and event detection
- Post-Event Processing:
  - Same data as In-Situ Processing
  - Data available from all other ESP's to learn and test mechanical health trend

2 Failure Onset Prediction for Event #2

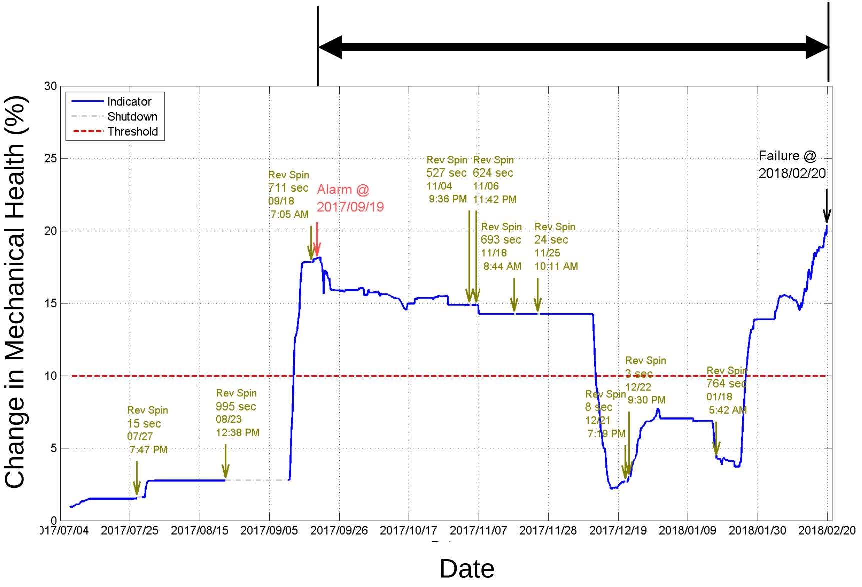
In-Situ

0 days lead



Post-Event

154 days lead



2 Observations on Mechanical Health Trending

- Evidence from the two failure events indicates
  - The in-situ measurements made for mechanical health trending appear effective
  - Processing algorithms are improving as more ESP operating history and events are made available to the learning system
  - Post-event analysis accounts for peculiarities not found on standard assets
- Evidence from the post-event analysis of the failure events shows
  - The single largest contributor to mechanical health degradation appears to be the shut-downs causing reverse rotation and/or the following start-ups
    - Must eliminate one of the two or both of these phenomena
  - Recording of a failure event on an ungrounded ESP with no reverse rotations and associated jumps in mechanical trend may help identify the next causal relation between mechanical health and possibly other adverse operating conditions

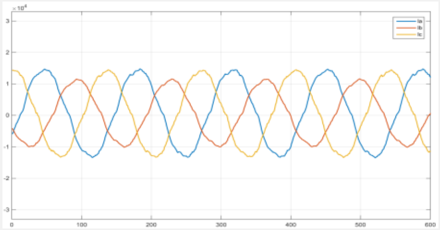
3 ESP Ground Fault Detection

- ESP-B installation during September 2016
  - Start-up of a new ESP-B
  - Monitoring turned on after ESP start-up
  - No other ESP monitored at the time
- First data sets received indicate the presence of a ground fault
  - GFIC triggered pump shutdown ~12 hours later from first indication of ground fault from EWM
- Pump is restarted and operating with ground fault
- Ground fault progression is being tracked by EWM; presently currents too high to measure accurately
- Phase-to-phase voltage waveforms normal

3 ESP Ground Fault Degradation

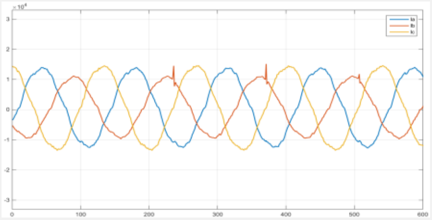
MONTH 1

The waveforms show a high degree of unbalance. The ungrounded phase currents (a, c) are within +/-2% of each other, while the grounded phase current (b) is 23% lower. This suggests that the ESP had some ground fault events prior to EWM installation



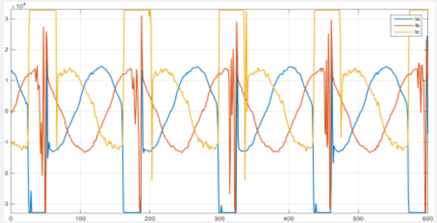
MONTH 3

For approximately 6 hours, there were phase current excursions beyond the expected operating range and harmonic distortion on phase current b was very high. The notches are indicative of likely arcing caused by the ground fault. The ungrounded phase currents (a, c) are within +/-5% of each other while the grounded phase current (b) is 25% lower.

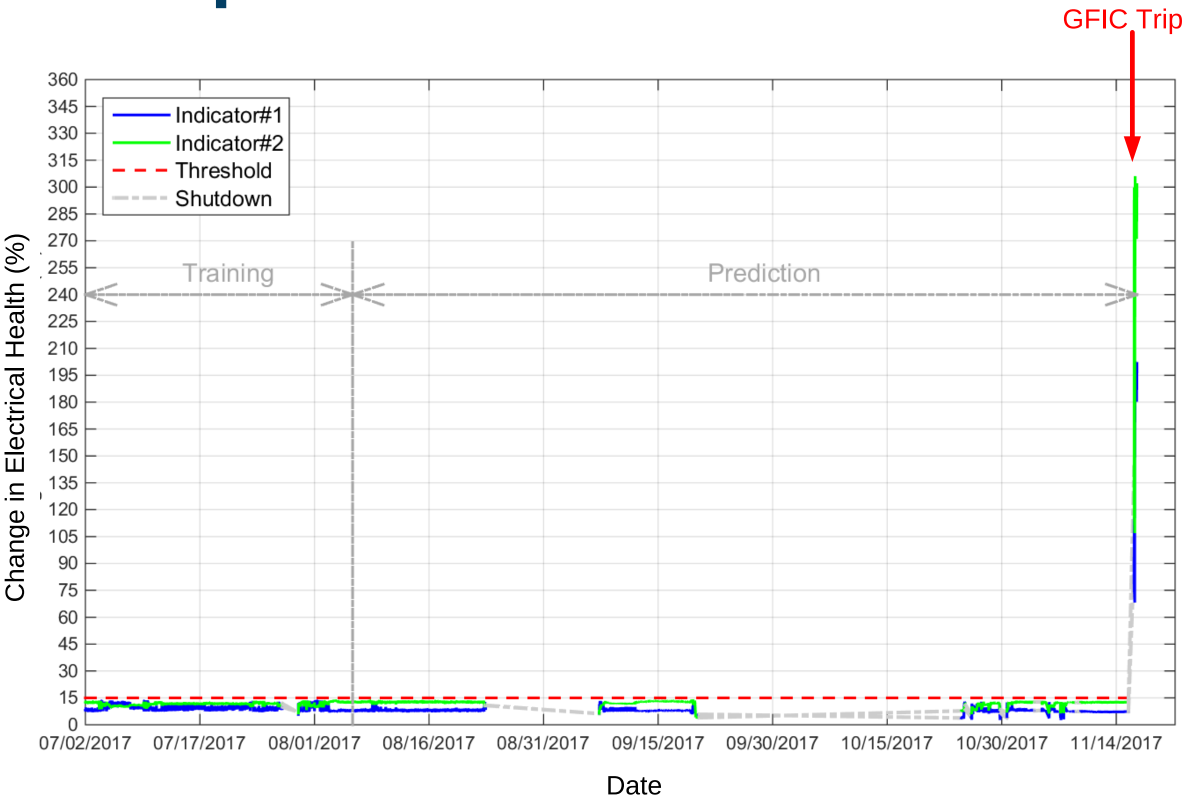


MONTH 8

After 8 months of operation, the ungrounded phase currents (a, c) are very high and exceed the EWM calibration and measurement range during 1/3 of each cycle. The grounded phase current (b) is now 35% lower than other two phases.



3 ESP GFIC Trip Event



- ❑ Electrical ground fault indicator high at GFIC trip.

Concluding Remarks

- **Impediments to ESP monitoring:**
  - Harsh operating environments limit feasibility of mechanical sensors that can provide condition information, e.g. vibration
  - Remote asset locations limit capability to make and communicate high frequency measurements
- **Key lessons from this case study:**
  - Topside non-intrusive electrical waveform measurements are feasible and provide valuable ESP condition insights
  - EWM analysis can help identify adverse operating anomalies such as:
    - Post-shutdown reverse rotation speed and duration
    - Mechanical condition abnormalities
    - Electrical ground fault degradation
  - EWM implementation allowed operations team make improvement in ESP system improvements to improve
  - Further ESP operational experience and event base is needed to mature the post-event analysis into more reliable ESP predictive capability