Smart Meter Data Analysis for Distribution Transformer Monitoring and Sizing

Valliappan Muthukaruppan
Sr. Data Scientist, Exelon Customer Analytics

Distribution Transformer Monitoring

Challenges

Unlike Power Transformers, distribution transformers do not have any monitoring in the existing system.

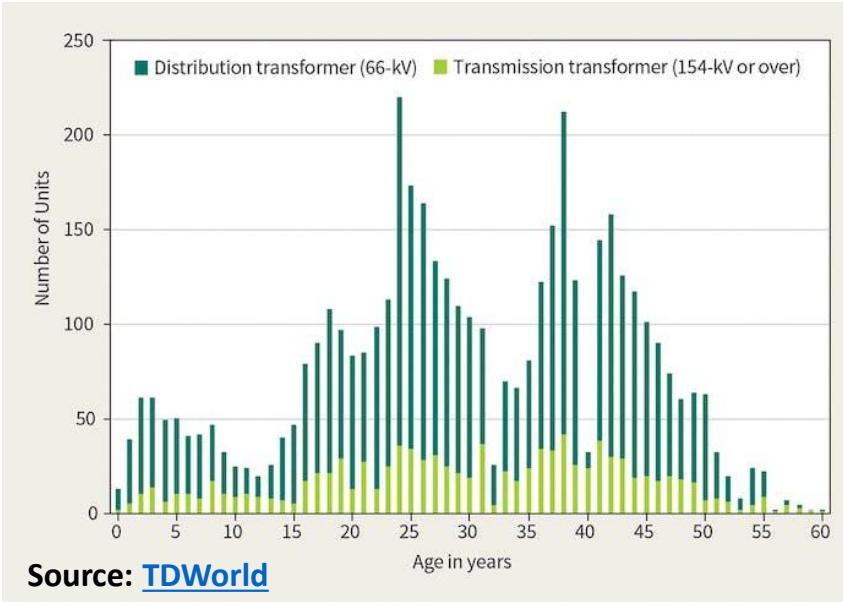
Motivation

Serious threat to existing transformers:

- Aging infrastructure.
- Changing customer load and behavior.
- Electrification.

Distribution Transformers

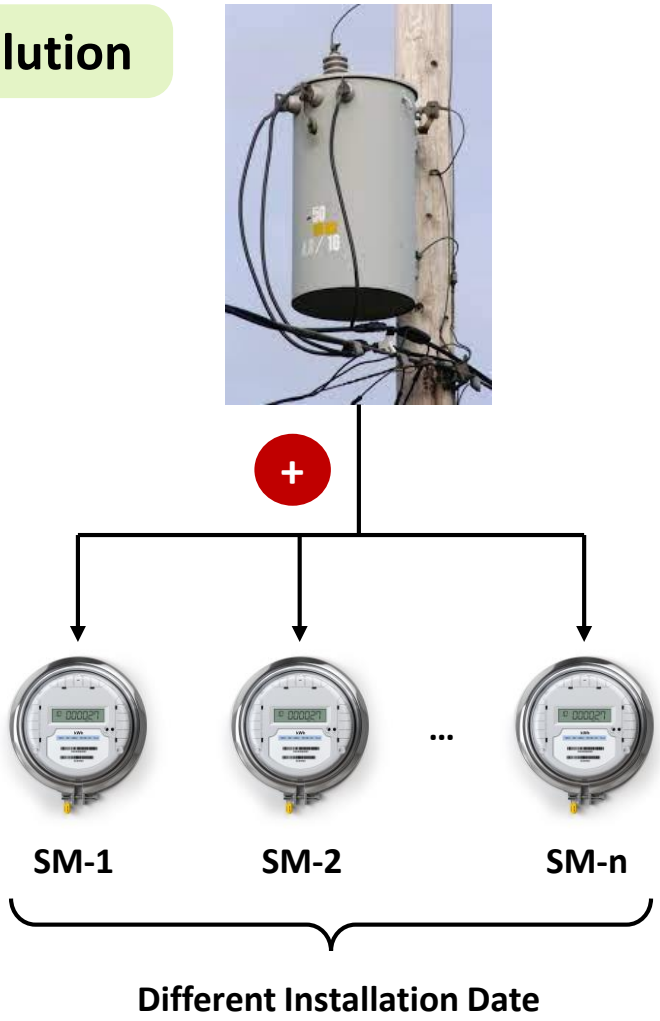




Source: TDWorld

Smart Meter Data for Monitoring

Solution



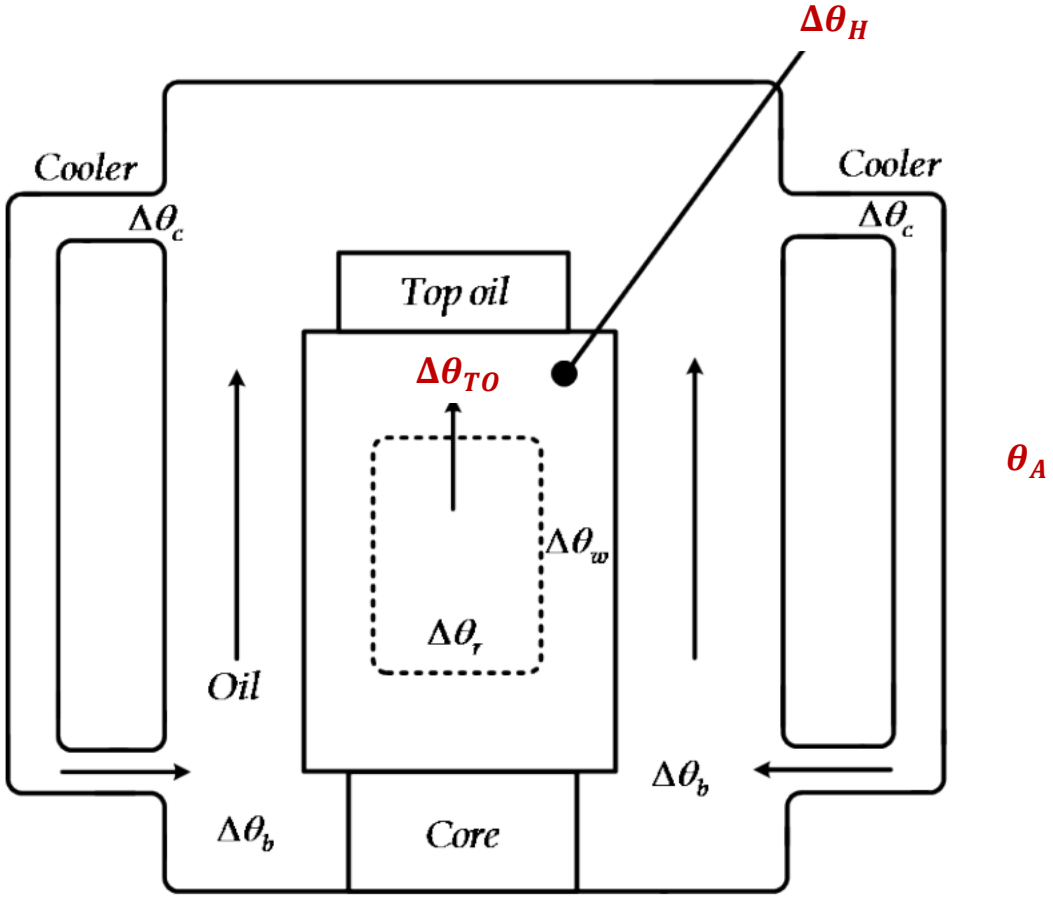
Challenges

- Distribution transformers are designed to be overloaded and are often overloaded without proper monitoring.
- Risk of overloading Oil-Immersed Transformers:
  - IEEE C57.91-2011
  - IEC 60076-7:2018
- Loading of transformer alone is not sufficient for monitoring distribution transformers.

IEEE C57.91 and IEC 60076-7 (better monitoring)

Exponential model to calculate Transformer internal temperature and Equivalent aging using transformer loading and ambient temperature data.

Transformer Temperature Model



Thermal Diagram of Oil Transformers

Ref: IEEE C57.91-2011

Definitions

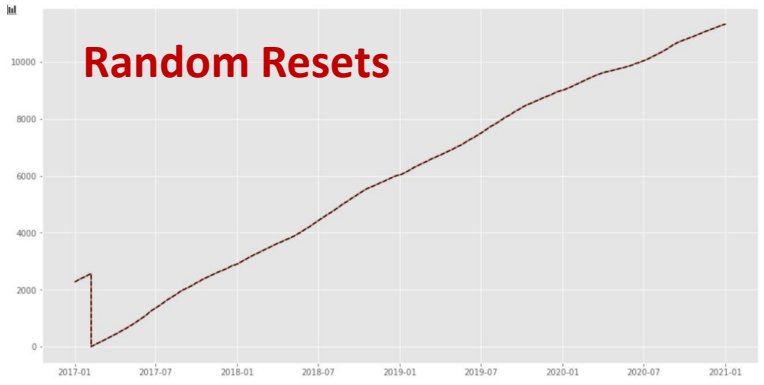
- $\boldsymbol{\theta_A}$ - Ambient Temperature $(^\circ C)$
- $\Delta\theta_{TO}$ - Top-oil Temperature rise over ambient temperature $(^\circ C)$
- $\Delta\theta_H$ - Winding Hottest-spot temperature rise over top-oil temperature $(^\circ C)$
- $\boldsymbol{\theta_{TO}}$ - Top-oil temperature $(^\circ C)$
- $\boldsymbol{\theta_H}$ - Winding hottest spot temperature $(^\circ C)$
- $\boldsymbol{F_{AA}}$ - Equivalent Aging $(p.u.)$

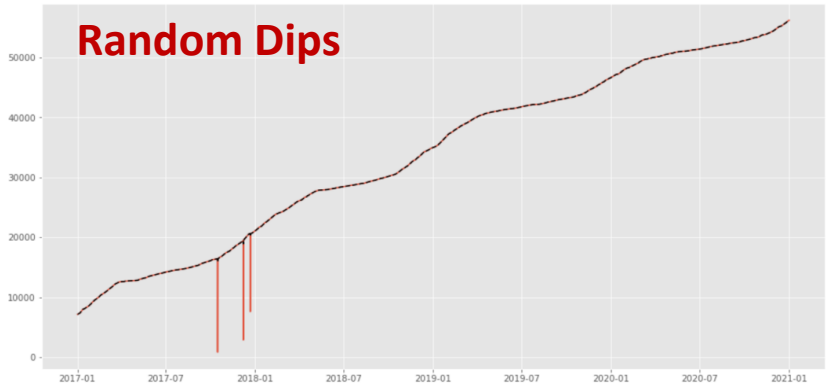
Formula

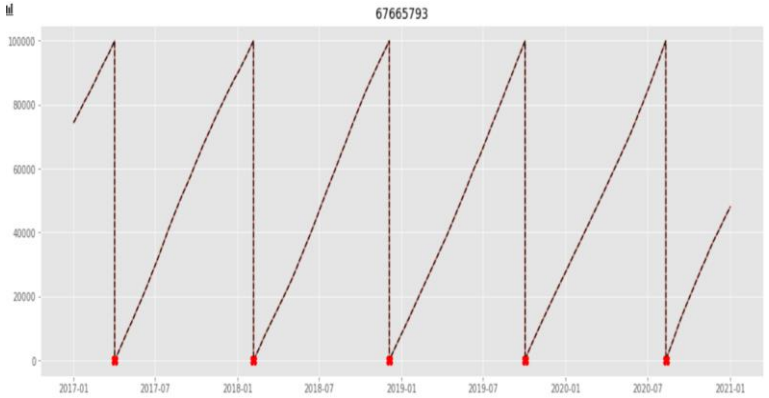
$$\theta_{TO} = \theta_A + \Delta\theta_{TO}$$
$$\theta_H = \theta_{TO} + \Delta\theta_H$$
$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]}$$

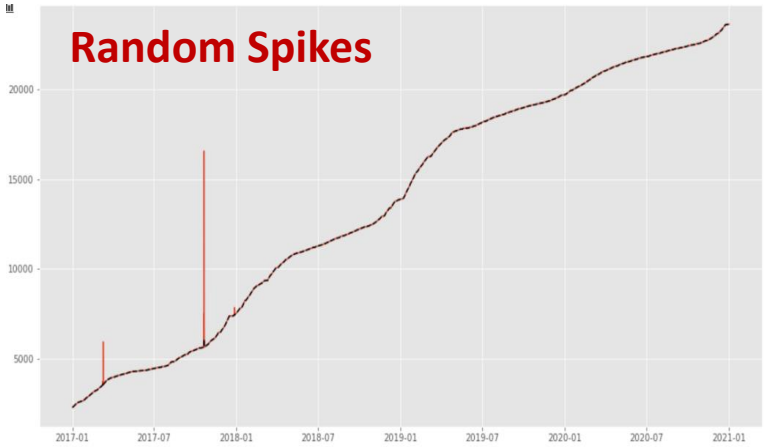
Depend on Transformer loading through exponential model.

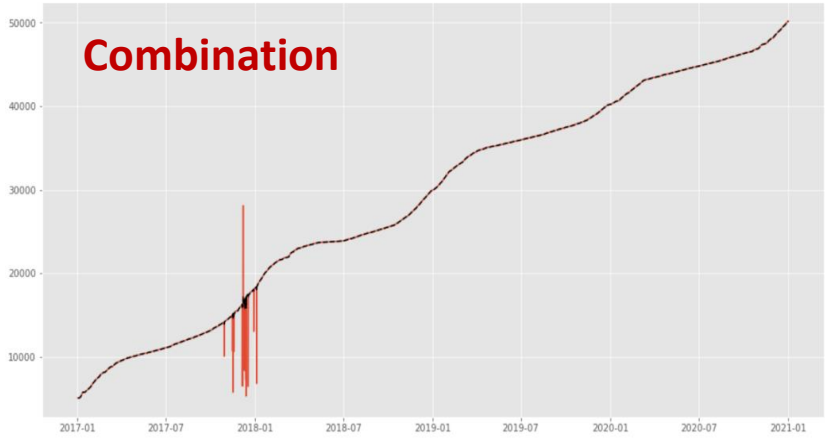
Smart Meter Data Quality Issues









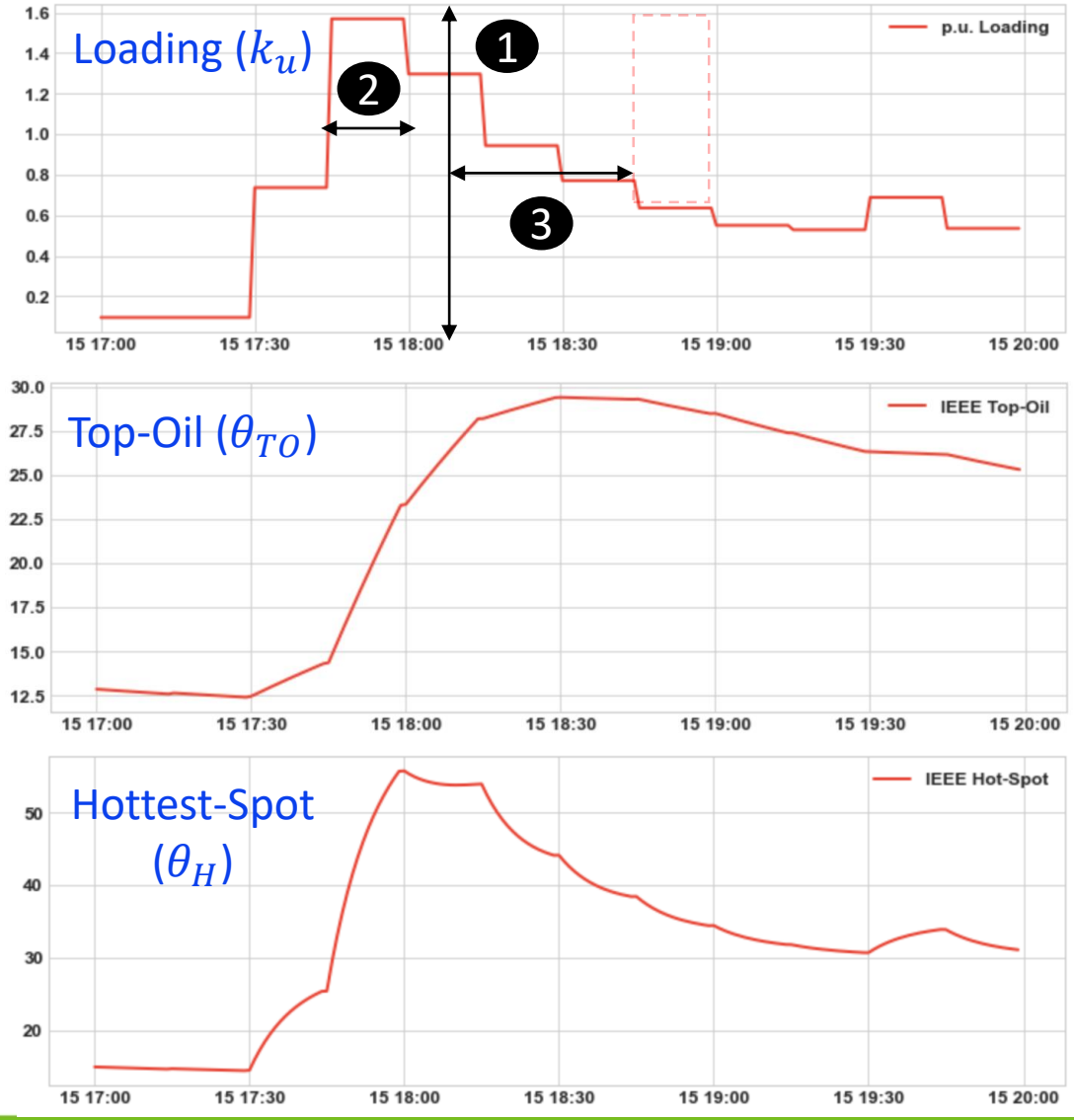


Challenges

Addressing data quality issues in smart meter data prior to analysis is critical.

Smart Meter Energy Measurements

Transformer Overloading



Parameters Impacting Temperature

- Ambient Temperature (θ_A)

1. Peak overload
2. Duration of overload
3. Duration between overloads

Transformer Aging

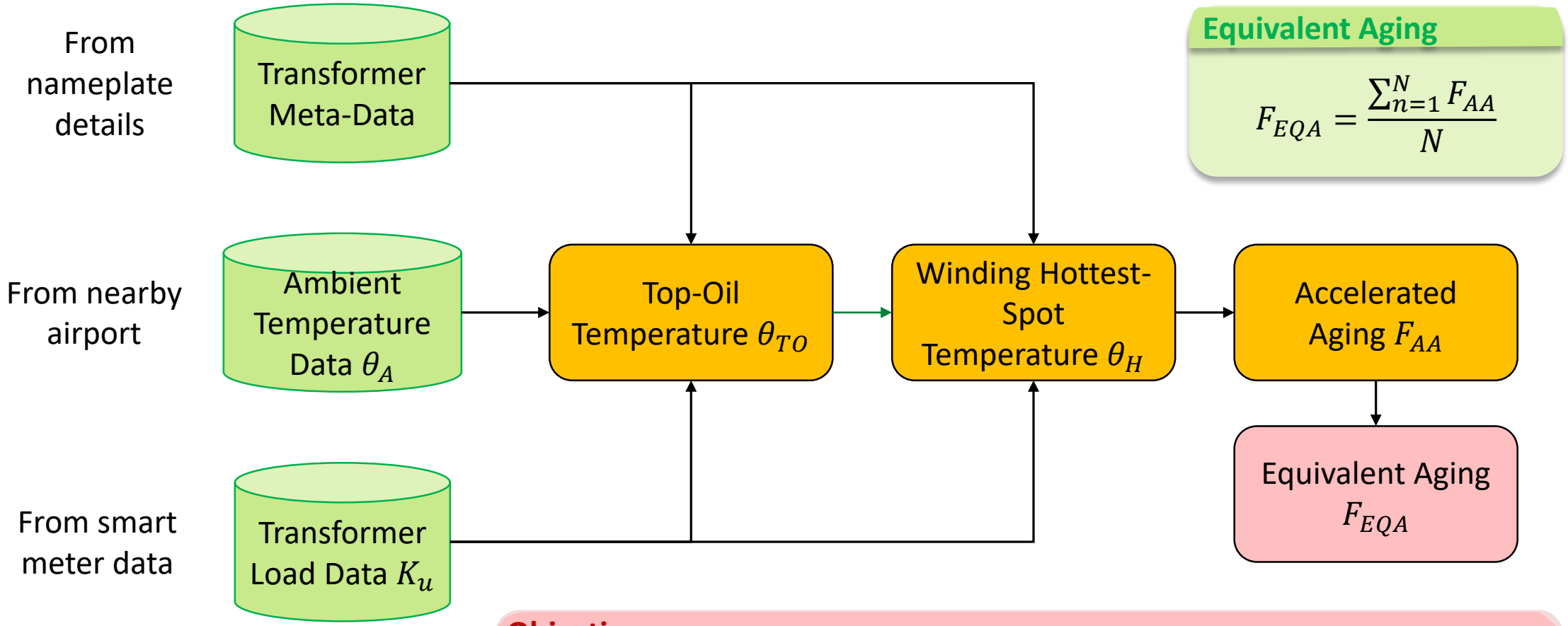
Transformer ages by 1-day on a natural day if $\theta_H = 110°C$.

$\theta_H > 110°C$ ➔ Accelerated Aging

Impacts of Overloading

- Increased probability of transformer failure.
- Reduced useful life of transformer.
- Exposed electrical components due to oil expulsion.

Overloading Analysis Tool



Equivalent Aging

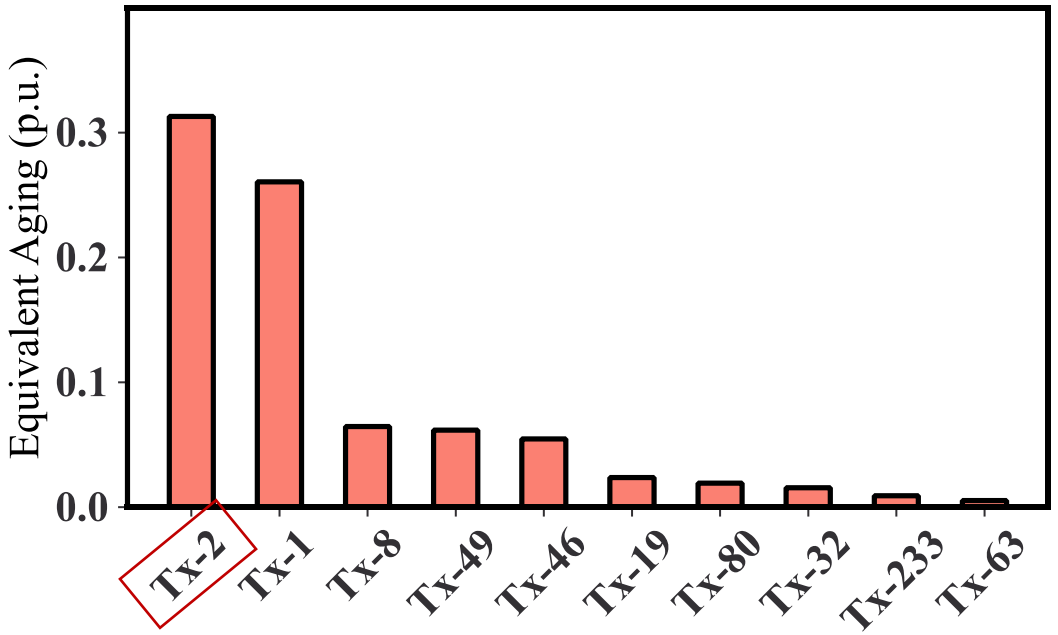
$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA}}{N}$$

Objective

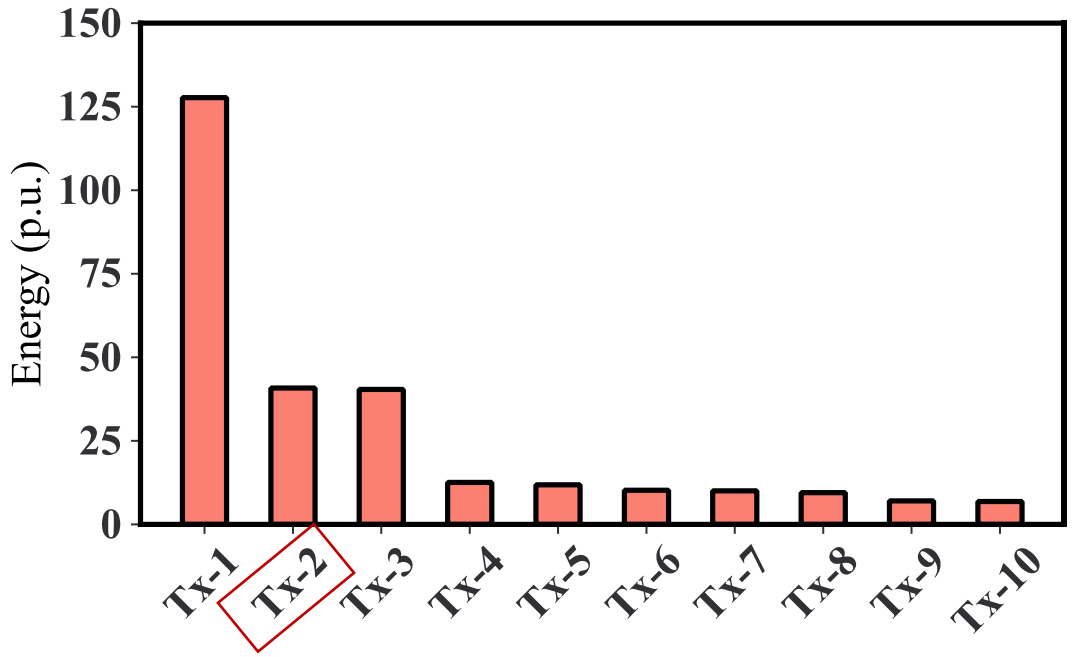
Given set of transformers ➔ Rank them based on severity of overload.
Tested on real world data with 1415 transformers.

Results

Proposed Strategy



Base Case



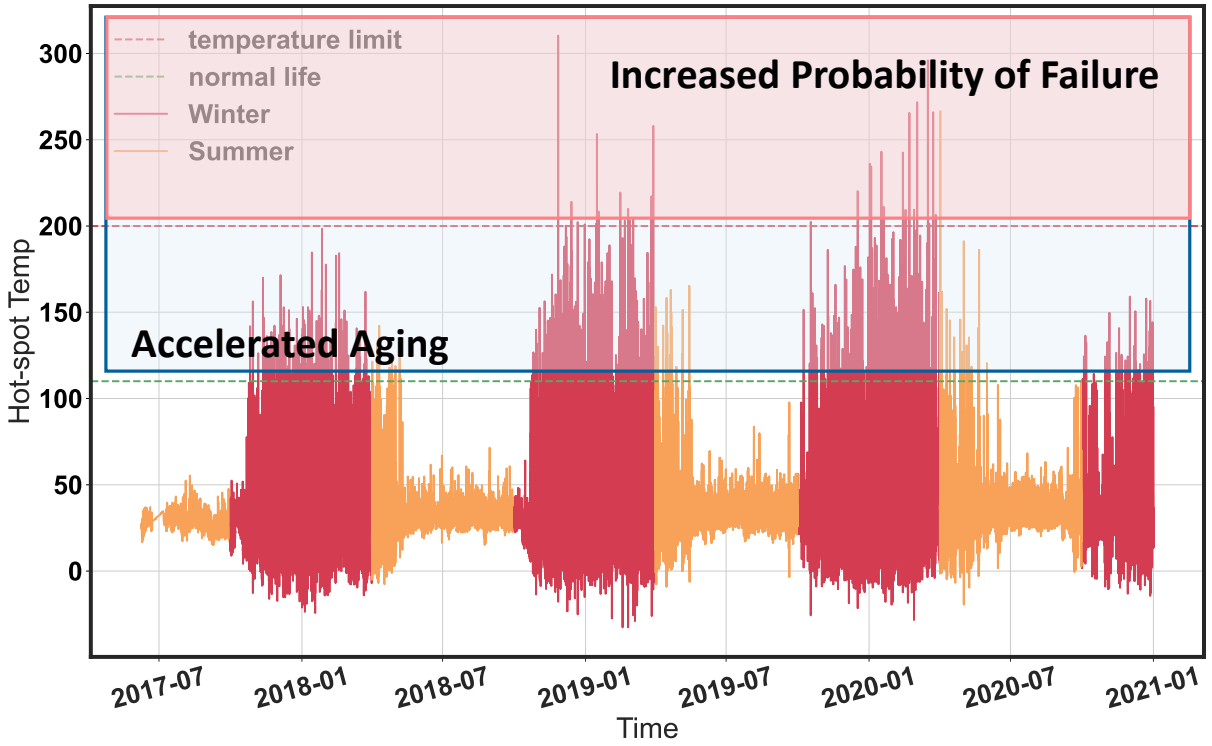
Inference

- Tx-2 is most overloaded according to F_{EQA} but only 2nd most overloaded according to OL_{energy}.
- OL_{energy} does not capture duration between overloads.

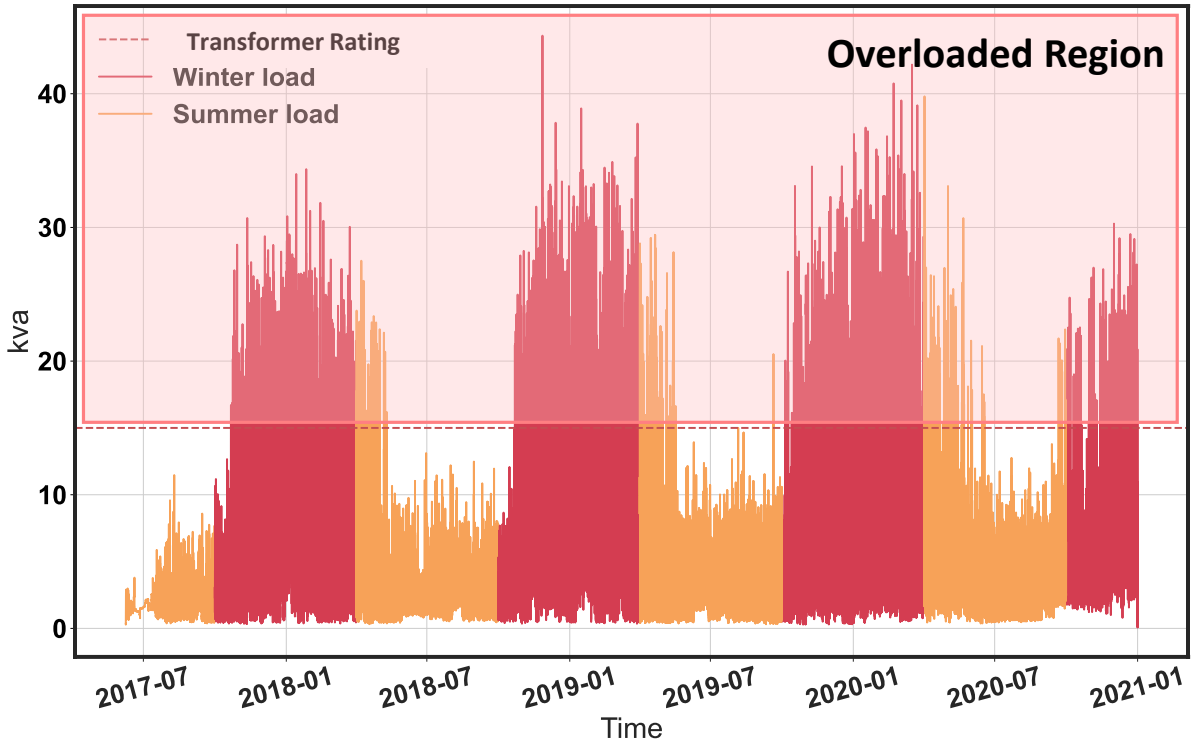
$$OL_{energy} = \frac{\sum_{t=0}^{T} \left(\frac{kva(t)}{rating} - 1 \right)_{\geq 0}}{\Delta t}$$

Tx-2 Loading and temperature

Hot-Spot Temperature



p.u. Loading



Inference

- ❖ Significant overloading (>2.0 p.u.) in the winter.
- ❖ Transformer still in operation after violating failure limits.

[1] V. Muthukaruppan, et. al., "Overloading Analysis of Distribution Transformers using Smart Meter Data", *IEEE ISGT*, 2022.

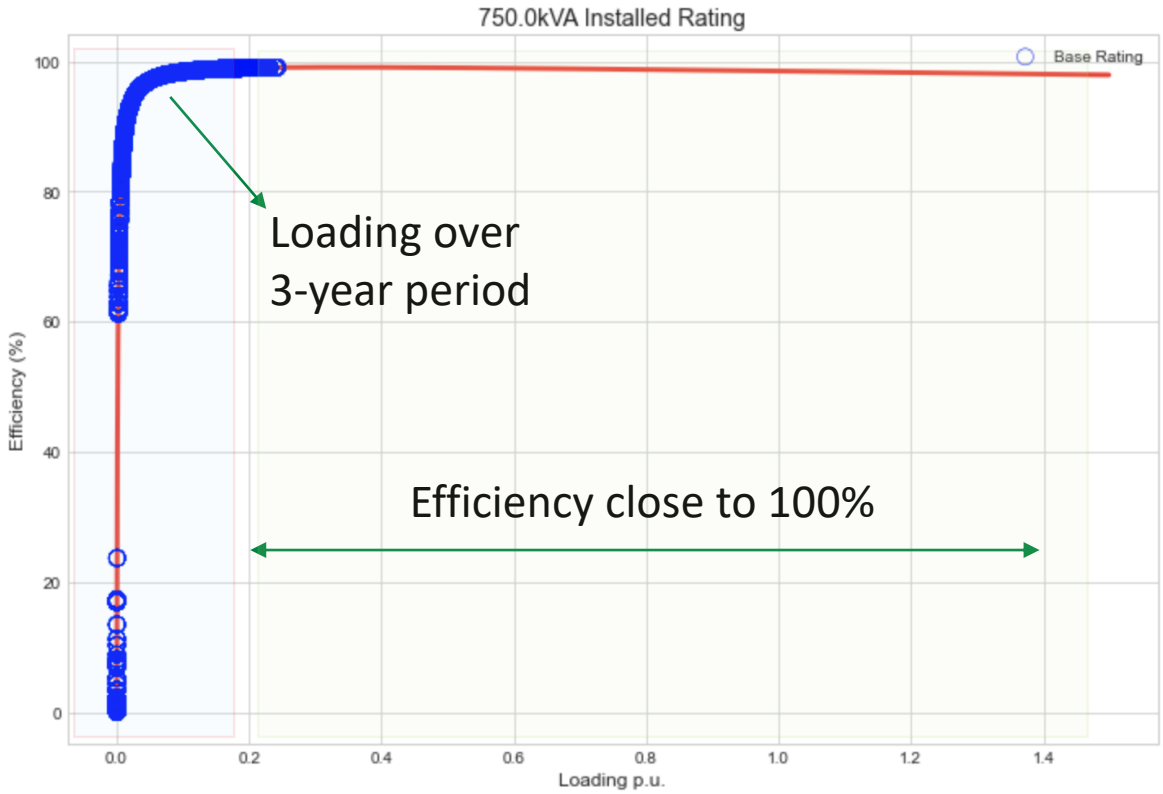
Severe Transformer Shortage

Problem

- US is suffering from severe shortage of transformers (small distribution to large power transformers)[1].
  - Bottleneck for grid modernization, electrification, and renewable integration.
  - Aggravated by aging infrastructure.

Opportunity

- Large apartment transformers with many smart meters are severely underloaded.
- Can be replaced with an appropriate size.
- Replacement requires detailed economic and risk analysis.

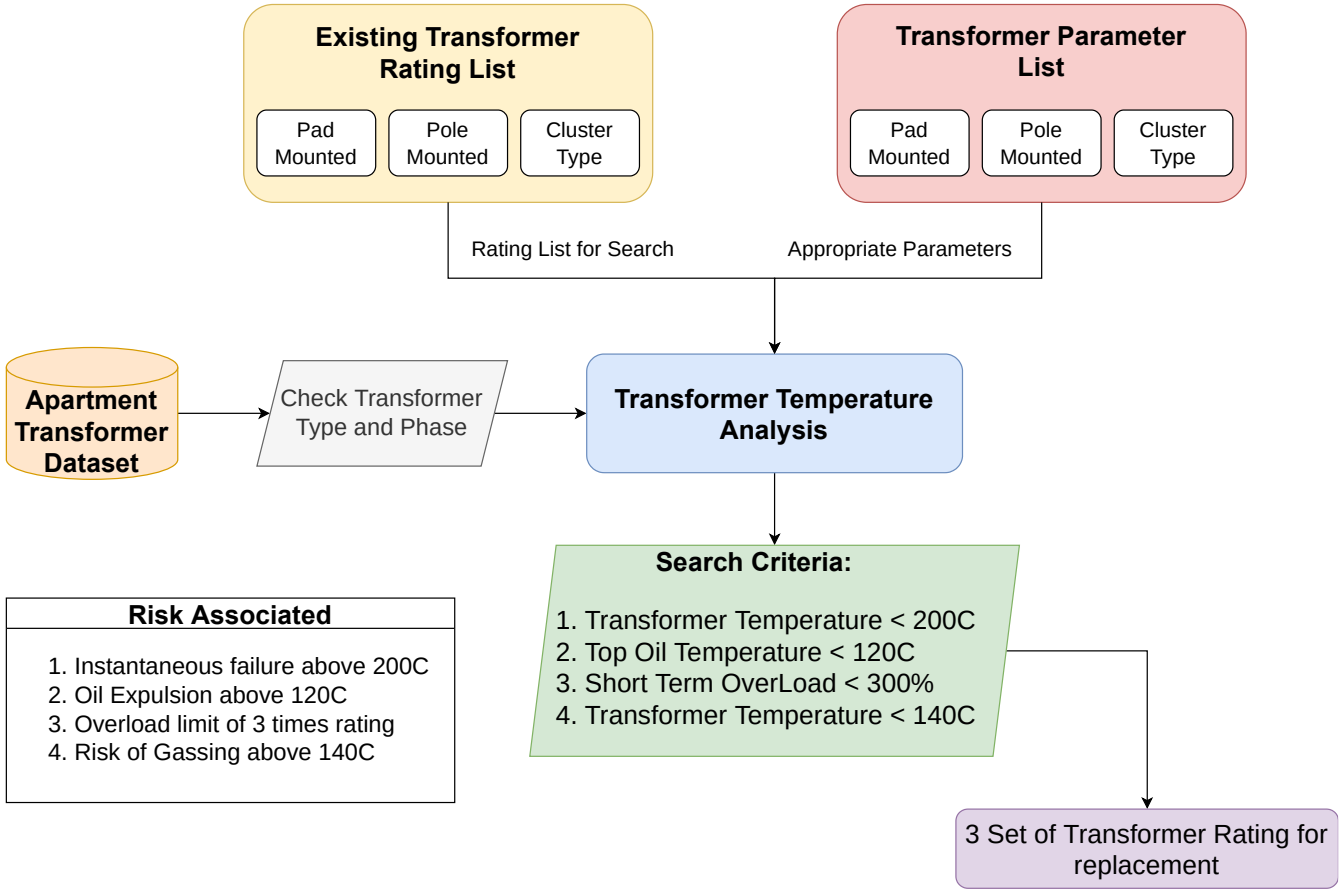


p.u. Loading vs Efficiency

Rating of Transformer: **750 kVA**
No. of Customers: **83**
Average Loading: **0.1153 p.u.**

[1] How a transformer shortage threatens the grid, Oct 2022 (Link)

Transformer Swap Tool

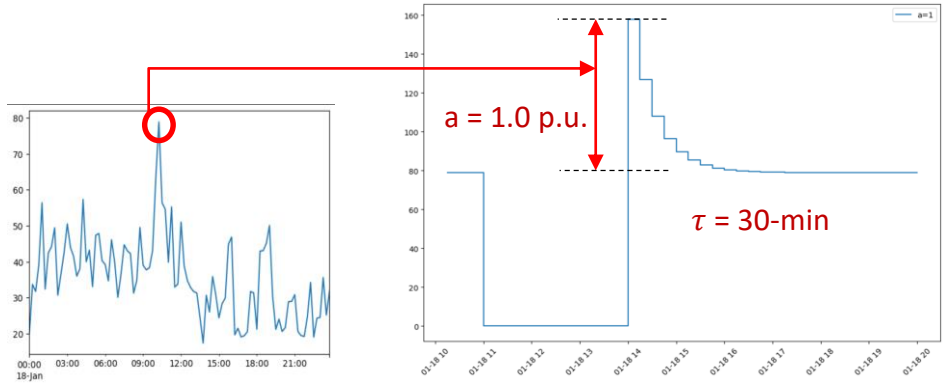


Risk Associated

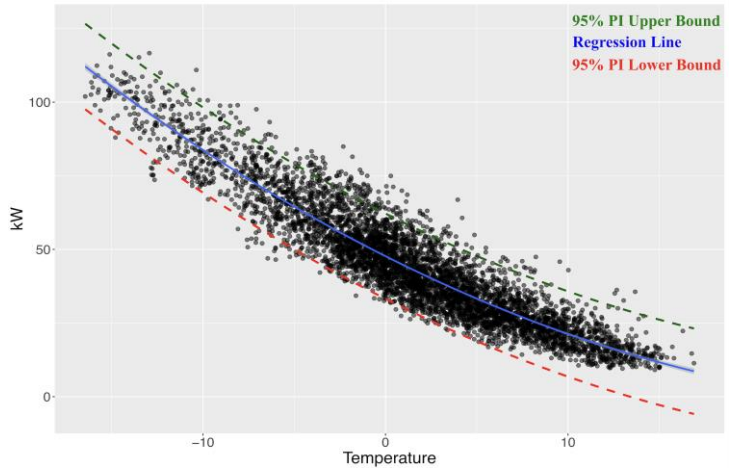
1. Instantaneous failure above 200C
2. Oil Expulsion above 120C
3. Overload limit of 3 times rating
4. Risk of Gassing above 140C

Search Based Planning Tool

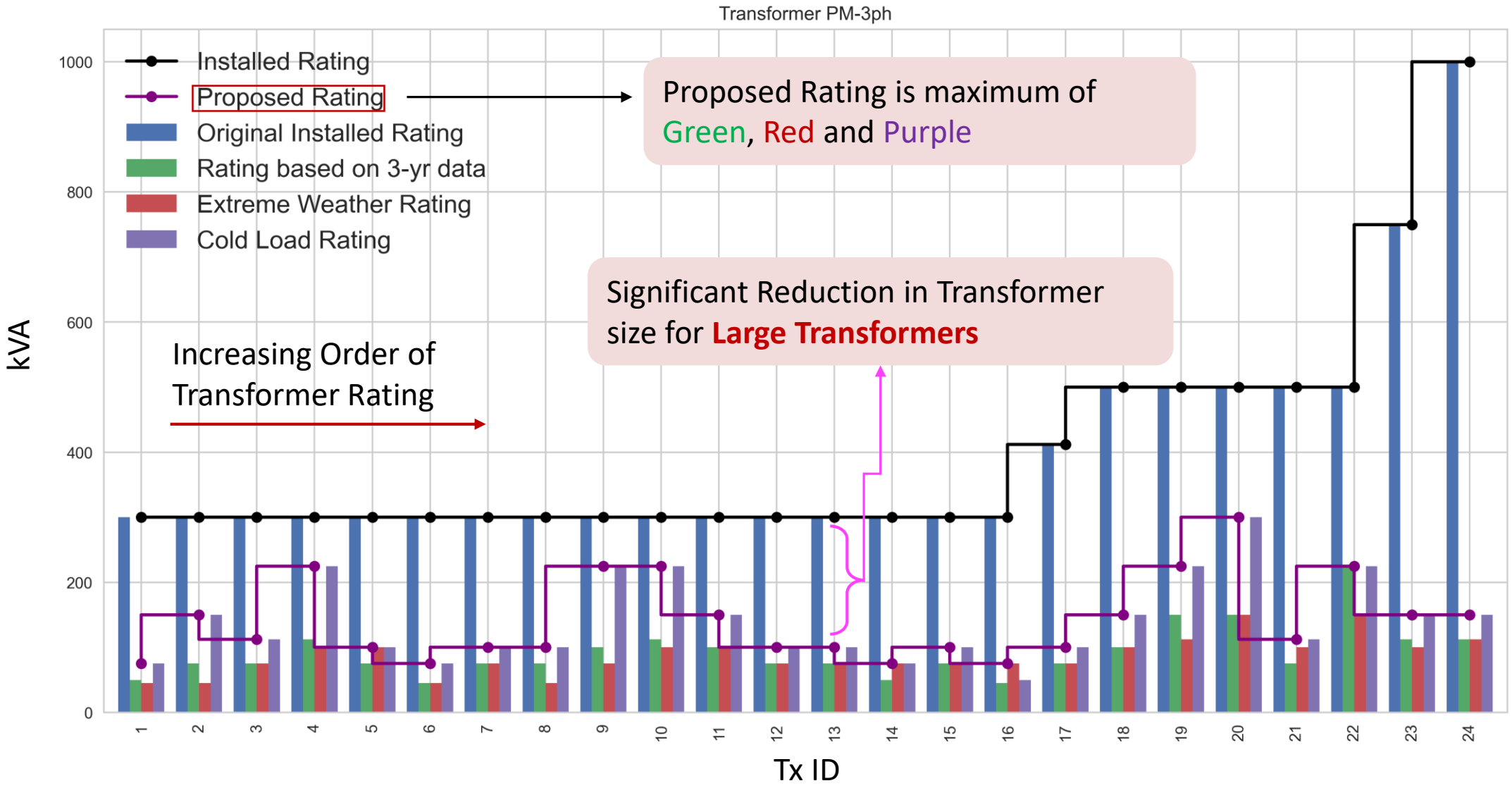
Simulated Cold Load PickUp



Simulated Load during Extreme Weather



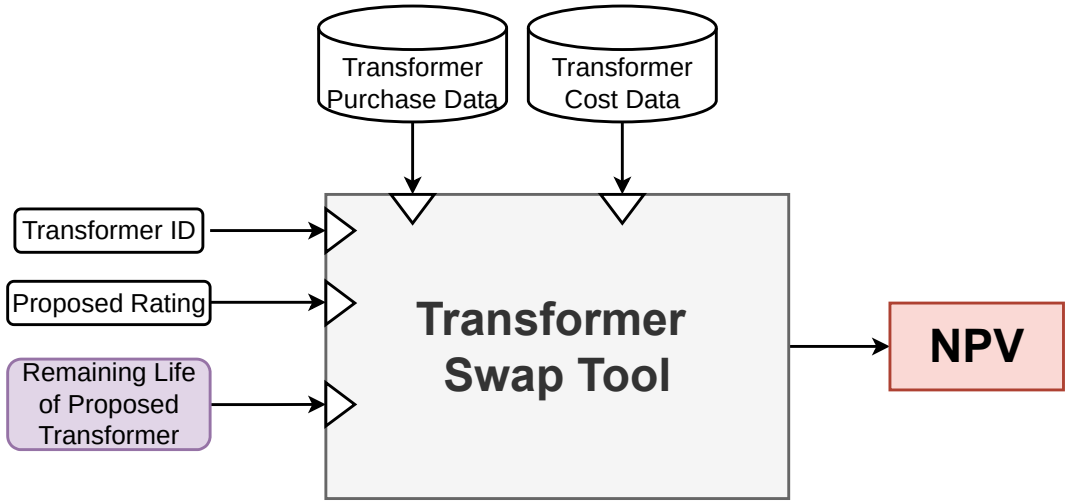
Results (Pad Mounted Tx)



Economic Impact of Tx Age

Challenge

- Utility will not purchase new transformer of smaller rating for replacement, must be available in stock
- Not all replacements make economic sense since transformer age has a significant impact.



Potential Usage of Tool

- For a given transformer can decide which of the available stock of replacement transformer will provide most benefit.
- For a range of transformer ratings installed (say 500kVA) and a replacement transformer in stock helps decide which transformer replacement will provide most benefit.

Inference

- If proposed rating is higher than installed rating, then no use in replacing the transformer.
- Newer the proposed transformer and older the original installed transformer higher the benefit in replacement.

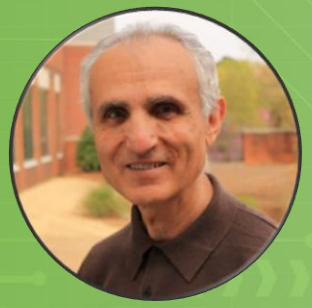
For more details refer to our previous webinar Smart Meter Data Analytics for Distribution Transformer Asset Management (link)

Conclusion and Future Work

- Three different data-driven tools:
  - Online monitoring and overloading analysis tool.
  - Underloaded Transformer replacement tool.
  - Cost benefit tool for swapping transformers.

- Future Direction
  - Electrification poses severe threat to distribution transformers.
  - Proposed tools can be easily extended to study impact of future electrification on transformers at different levels of the circuit.

Valliappan Muthukaruppan (NCSU)



Dr. Mesut Baran *Professor* (NCSU)

Dr. Ning Lu *Professor* (NCSU)

PJ Rehm *Manager (Electricities)*

Matthew Makdad *Engineering Supervisor (NRLP)*

Ed Miller Manager *(NRLP)*

Thank You

Contact: vmuthuk4@gmail.com