Digital Twins for Distribution Transformers and Overhead Conductors to Improve Quality of Service Under Faults and Fire Risk

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Introductions

• What keeps me up at night?

  Wide integration & seamless operation of (volatile) renewables in electrical grids

• How do I make what I care about possible?

  Control, system modeling, optimization, heuristic methods (AI & ML), standards

• Who am I working with?

  X, REN, Dept. of Energy, NYISO, Duquesne, Depsys, VT-IoT, Xeal, IEEE, IET, NASPI
Outline

• *Introduction*: Motivation for Active Distribution Networks

• *Part 1:*
  Digital Twin of Distribution Transformer

• *Part 2:*
  Wildfire detection with the Digital Twin of Overhead Conductor

• *Conclusion & Path Forward*
"Electricity customers in the US have not been suffering service disruptions, but for some local rolling blackouts in CA & TX under extreme conditions" #energy #infrastructure
What is wrong with the grid?

• Designed to operate under (some) faulty conditions
  o (Some) Faults go unnoticed until additional faults pile up

• Poor equipment maintenance and vegetation (surroundings) control
  o Reasons for faults left unchecked

• No digital models, poor monitoring & automation (TX rolling blackouts...)

• Renewables arbitrarily installed & passively operated

• Not properly restructured business

  *Much of the grid built per the “fit & forget” or “fail gracefully” strategies...*
So we need active distribution grids...
What does the industry think about that?
Digital Twin of Distribution Transformer

Real Time Fault and Power Quality Monitoring
Some necessary background – Grid Design

- AC power travels long with fewer losses at higher voltage
- Most typical devices, motors and generators barely operate at medium voltage (size, protection, etc)

![Diagram of grid with generator, step-up transformer, line, and step-down transformer to load.]
Some necessary background – Transformer Vector Groups & Grounding

• Transformers (T/F) increase/decrease voltage levels by inducting power between a shorter coil (low side) and a longer coil (high side)

• 1-phase is simple, but 3-phase T/F is not:
  o 1-phase T/F = 1 coil on each T/F side (high & low)
  o 3-phase T/F = 3 coils on each T/F side
  o 3 coils/ phases can be connected either in star or delta
  o The two 3-coiled T/F sides can change voltage phase
  o Star connection has a neutral that could be grounded
Distribution grid design with transformers

• Some 3-phase transformers (T/F) vector groups can operate at reduced capacity with one phase of one side at fault
• From circuit theory, a Delta-Star T/F with ungrounded neutral will not propagate line-ground (LG) and LLG faults from Delta to Star side
• A preferred Medium Voltage (MV) and LV architecture for distribution

Not all grid faults & designs are ‘kind’! Also pessimistic & risky!..
Can we capture faults in distribution grids in real time?

• The idea of the digital twin of a distribution T/F

• The value of distribution T/F digital twin:
  o Low voltage (LV) is directly monitored
  o MV is estimated
  o Possibly monitor other concerns?
  o Minimum disruption compared to other methods
Defining the digital twin of a single-phase distribution transformer (T/F)

• (a) > (b) > (c) T/F circuits by order of detail
• Preferring (b) circuit

\[
\begin{align*}
    u_2(t) &= u'_1(t) + R_S i'_1(t) + L_S \frac{di'_1(t)}{dt} \\
i_2(t) &= \frac{u_2(t)}{R_M} + \frac{1}{L_M} \int u_2(t) \, dt + i'_1(t) \\
u_2[n] &= u'_1[n] + R_S i'_1[n] + L_S (i'_1[n] - i'_1[n-1]) f_s \\
i_2[n] &= \frac{u_2[n]}{R_M} + \frac{u_2[n] - u_2[n-1]}{L_M \cdot f_s} + i'_1[n]
\end{align*}
\]

1: LV side, 2: MV side
Extending to the digital twin of 3-phase distribution transformers

\[ u_2[n] = u_1'[n] + R_s i_1'[n] + L_s (i_1'[n] - i_1'[n-1]) f_s \]

\[ i_2[n] = \frac{u_2[n]}{R_M} + \frac{u_2[n] - u_2[n-1]}{L_s f_s} + i_1'[n] \]

One set for each phase

Yy0: \( u_A = u_{2A} \) and \( i_A = i_{2A} \)

Dy1: \( u_{AB} \cdot \sqrt{3} = u_{2A} - u_{2C} \) and \( i_A = i_{2A} - i_{2C} \)

Dy11: \( u_{AB} \cdot \sqrt{3} = u_{2A} - u_{2B} \) and \( i_A = i_{2A} - i_{2B} \)
Testing the transformer (T/F) digital twin (1/2)

• Medium Voltage (MV) digital twin with comparable accuracy to instrument T/F under non-transient conditions:

• All transient (but very few) properly captured:
Testing the transformer (T/F) digital twin (2/2)

- Monitoring power quality – what are harmonics?
- The T/F circuit as a low-pass voltage filter

- There is no significant loss of accuracy between T/F and its digital twin for voltage harmonics
Publications & Funding

Wildfire detection for non-preemptive disconnection of overhead lines

And keeping the lights on, under challenging circumstances...
Electricity stakeholders’ role & response to fires

**DEEP DIVE**

*Wildfires pushed PG&E into bankruptcy. Should other utilities be worried?*

Catastrophic wildfires, which can lead to billions of dollars in damages, present a unique financial risk that the utility sector will want to get ahead of, experts say.

Published Nov. 19, 2020
Some Necessary Definitions – Active Power

• Energy ($E$) & Active Power ($P$)
  - Whatever moves, heats & charges
  - $P = \frac{\partial E}{\partial t}$

• Voltage Phase Angle ($\theta$)
  - Measure of active power flow over a mostly inductive line (transmission)
More Necessary Definitions – Reactive Power

• Why does voltage drop and, thus, causes concerns about its levels?
  o Ohm’s law of drop of voltage over an impedance run by current

• I.e. because we transmit power over lines...
  o Transmission line reactance much greater than resistance
  o Resistance → line losses in $P$, Reactance → line losses in reactive power $Q$

• Voltage magnitude ($|V|$)
  o Its drop caused mostly by the line induction (transmission)
The value of synchronized, real-time measurement of electrical grid operation

- Devices capturing the time-varying signals of voltage & current
- Named “Phasor MU” because they determine the phase angle of signals
- Simplified description of a PMU: ‘repurposed oscilloscope’
- Standardized equipment (e.g. IEEE Std C37.118.1 - new update coming)
Non-preemptive disconnection of lines – Idea
Impedance of a conductor

- Impedance includes resistance (affected by temperature) & reactance

\[
Z(T_c) = R(T_c) + jX = |Z(T_c)|\cos\delta(T_c) + j|Z(T_c)|\sin\delta(T_c)
\]
Relationship of Resistance to Ambient Temperature

- Particularly complicated
- But standardized
  - $Rl^2$ effect of line loading per se
  - $q_s$ effect from solar irradiation
  - $q_c$ exchange of heat load with surroundings
  - $q_r$ radiated heat loss
  - $T_a$ ambient temperature

\[
R(T_c) = R_{ref} \cdot [1 + \alpha(T_c - T_{c,ref})]
\]

\[
\frac{dT_c}{dt_T} = \frac{1}{m \cdot C_p} [R(T_c) \cdot l^2 + q_s - q_c(V_w, T_s, T_a) - q_r(T_s, T_a)]
\]
Effect of fire to ambient temperature

• Non-trivial relationship – Looking for assistance/expertise! (contact me)
• Function of fuel of fire, distance from a point of measurement and duration of the fire at a given intensity
• For a moss pine forest with several trees

<table>
<thead>
<tr>
<th>( t_F ) (s)</th>
<th>( d ) (m)</th>
<th>( \Delta T_a )(^{\circ}K\ or\ ^{\circ}C)</th>
<th>( t_F ) (s)</th>
<th>( d ) (m)</th>
<th>( \Delta T_a )(^{\circ}K\ or\ ^{\circ}C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>50</td>
<td>8.23 ( \cdot 10^{-3} )</td>
<td>10</td>
<td>30.99</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1.42 ( \cdot 10^4 )</td>
<td>30</td>
<td>53.69</td>
<td></td>
<td></td>
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<tr>
<td>60</td>
<td>2.02 ( \cdot 10^4 )</td>
<td>60</td>
<td>75.93</td>
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<tr>
<td>10</td>
<td>5.81</td>
<td>10</td>
<td>71.61</td>
<td></td>
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<tr>
<td>30</td>
<td>10.06</td>
<td>30</td>
<td>124.03</td>
<td></td>
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</tr>
<tr>
<td>60</td>
<td>14.23</td>
<td>60</td>
<td>175.40</td>
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</tbody>
</table>
Method of detecting approaching forest fire through line impedance

\[ Z(T_c) = R(T_c) + jX = |Z(T_c)| \cos \delta(T_c) + j|Z(T_c)| \sin \delta(T_c) \]

• It is \( \tan(\delta(T_c)) = \frac{X}{R(T_c)} \)

• \( \tan(\delta) \) may be estimated from electrical measurements as:

\[
\tan \delta = \frac{P_R V_S \sin \theta + Q_R V_S \cos \theta - Q_R V_R}{P_R V_S \cos \theta - Q_R V_S \sin \theta - P_R V_R}
\]
How should the method operate – and not...

- Moving average tanδ at $\Delta T_a = 132^\circ C$
- Slope of moving average tanδ at $\Delta T_a = 132^\circ C$

- Moving average tanδ at $\Delta T_a = 29^\circ C$
- Slope of moving average tanδ at $\Delta T_a = 29^\circ C$
Extensive statistical testing to assess

1. Distances of the fire seat from the overhead line of at most 50m, burning for at least 10s, which, as of Table, corresponds to $\Delta T_a$ between 0-225.5 °C (including no fire),
2. Ambient temperature $T_a$ ahead of the effect of the fire between 10-40 °C,
3. Wind speed $V_w$ between 0-6.5 m/s,
4. Conductor surface temperature $T_s$ between 10-100 °C,
5. Lengths of part $S-R$ of the line up to 20km,
6. Line current up to 1600 Amps (considering also step load increase or decrease),
7. Reactive power compensation with switching capacitor banks at the load bus for power factor correction up to 1,
8. PMU voltage measurement error up to 0.001 p.u. and
9. PMU current measurement error up to 0.01 p.u.

• Results assessed and classified with decision trees (machine learning)
Control Parametrization & Conditions of Detection – *In Silico*

- Control parametrization capturing fire approach in 0.1 s
- Conditions to capture fire approach from decision tree inference:
  - 86% of the cases with fire burning for at least 60 s at a distance of at most 5 m from the conductor,
  - 100% of the cases with $V_{w}<1.35\text{m/s}$ and line loading $>90\%$ and
  - 94% of the cases with $T_{s}<57\text{oC}$, line loading $>50\%$ of the line static rating and fire burning for at least 10 s at a distance of at most 10 m from the conductor.
Performance (False Positives, Timing Loss & Delay, Capacitor Switching) – *In Silico*

<table>
<thead>
<tr>
<th>Control type &amp; conditions</th>
<th>$\Delta$tan$\delta$ performance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 1 with $\Delta T &gt; 2.87^{\circ}$C</td>
<td>TP</td>
</tr>
<tr>
<td>99.32</td>
<td>0.29</td>
</tr>
<tr>
<td>Control 2 with $\Delta T &gt; 2.87^{\circ}$C and $V_{en} &lt; 0.003%$</td>
<td>89.13</td>
</tr>
</tbody>
</table>
Publications

Conclusions & Path Forward
Conclusions & Path Forward

• Passive and poorly monitored electrical grids are problematic
• Monitoring with digital twins and some automation are necessary
• Avoiding preemptive disruption of end-customer’ service
• Shortening fault intervention times & fault preparation
• Fault recording & learning phenomena
Thanks for your attention!

Questions, please?

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