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

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NASPI WG meeting – Oct. 19th, 2022

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Thanks for all the advice on this work, NASPI!

Introductions

- What keeps me up at night?

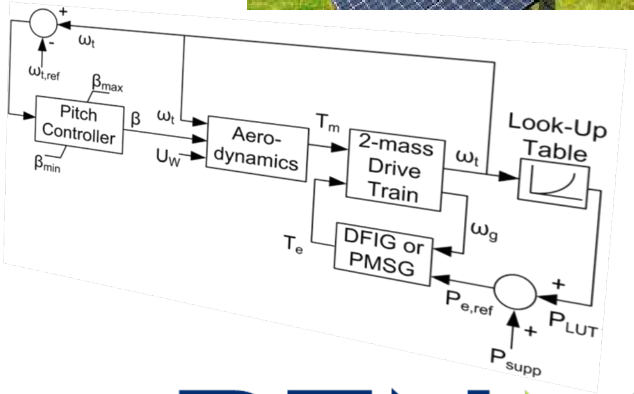
  Wide integration & *seamless* operation of (volatile) renewables in electrical grids

- 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



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Thanks for all the advice on this work, 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*

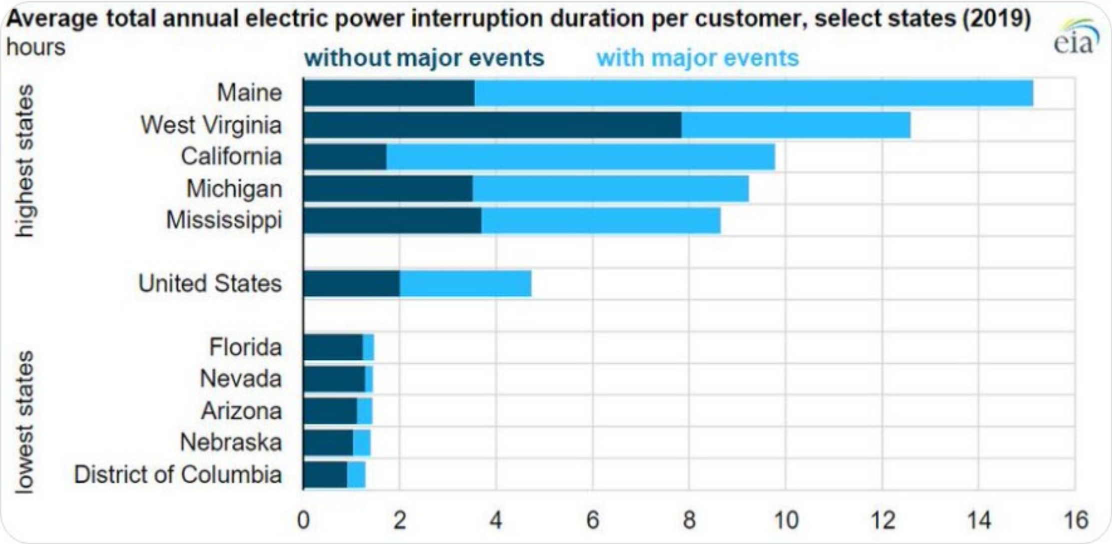
Thanks for all the advice on this work, NASPI!

The Electrical Grid is *not* OK…

Panayiotis (Panos) Moutis
@PMoutis

"#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 🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩🚩

10:29 AM · Oct 16, 2021 · Twitter Web App



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Thanks for all the advice on this work, NASPI!

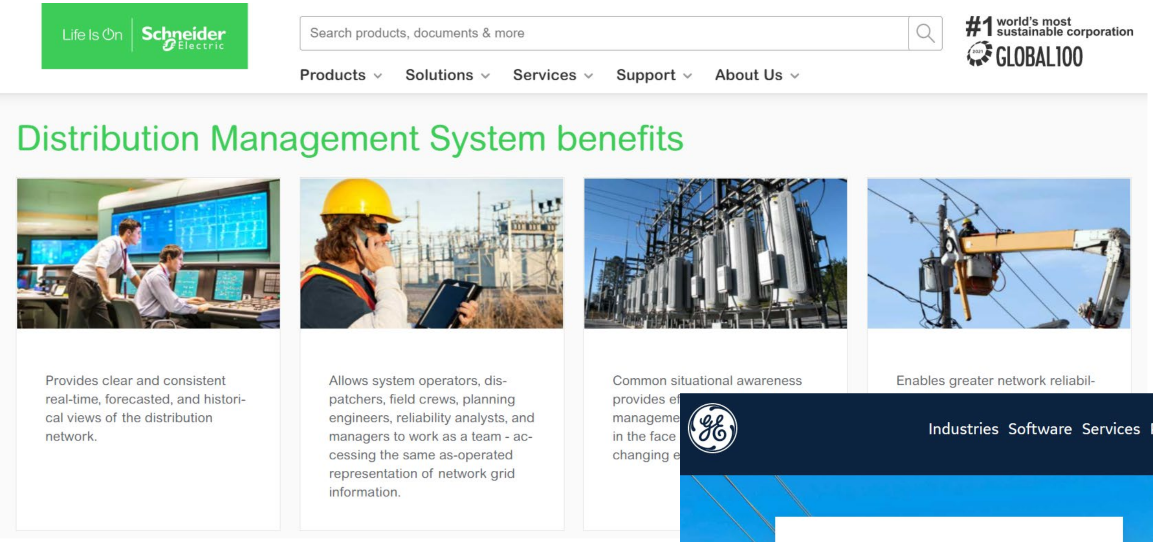
What is wrong with the grid?

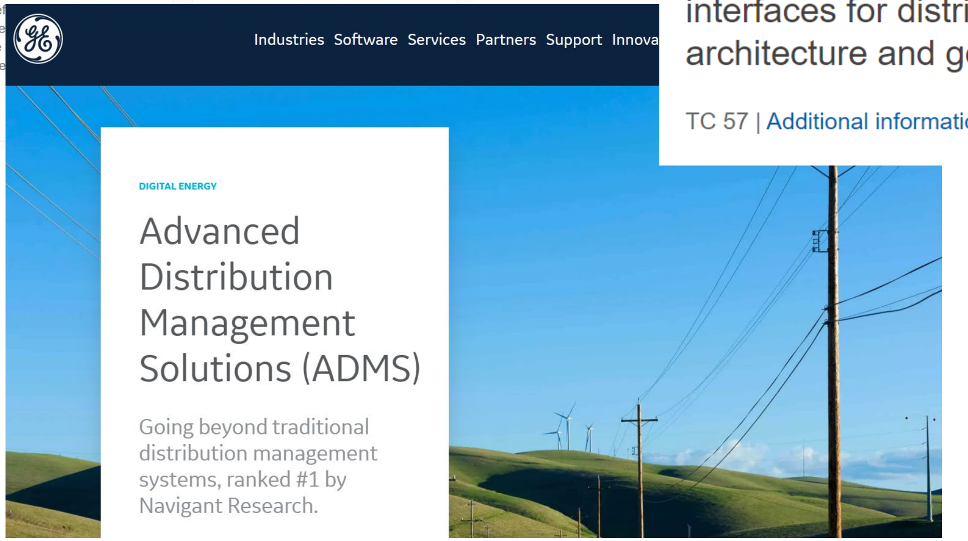
- Designed to operate under (some) faulty conditions
    - (Some) Faults go unnoticed until additional faults pile up
- Poor equipment maintenance and vegetation (surroundings) control
    - Reasons for faults left unchecked
- No digital models, poor monitoring & automation (TX rolling blackouts…)
- Renewables arbitrarily installed & passively operated
- Not properly restructured business

Much of the grid built per the “fit & forget” or “fail gracefully” strategies…

Thanks for all
the advice on
this work, NASPI!

So we need active distribution grids…
What does the industry think about that?





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Digital Twin of Distribution Transformer

Real Time Fault and Power Quality Monitoring

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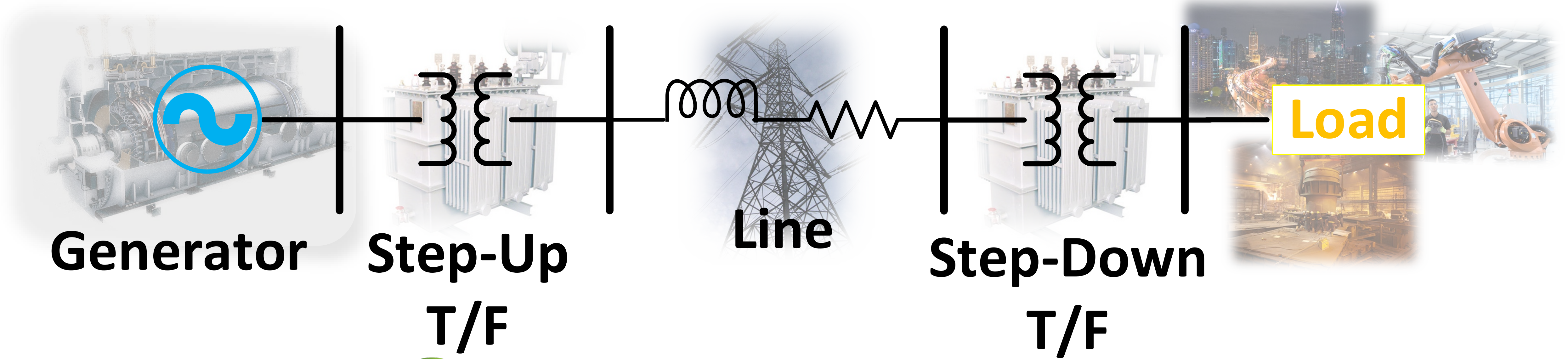
Some necessary background – Grid Design

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



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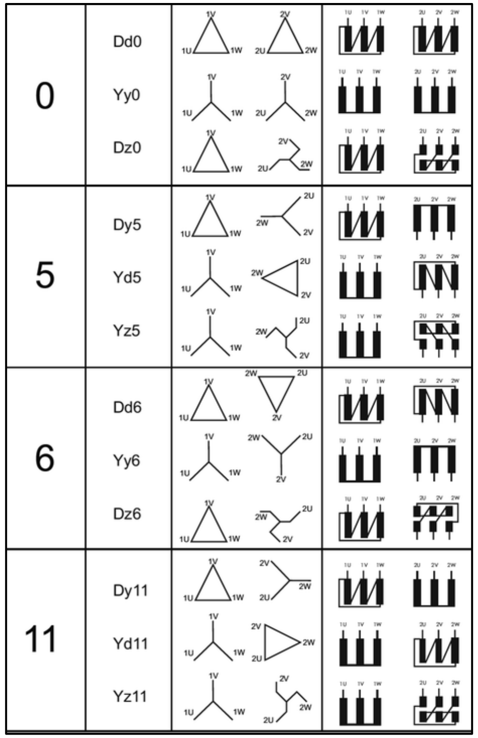
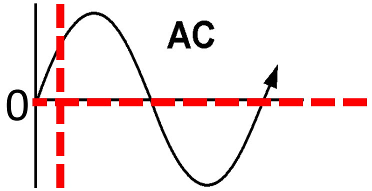
Thanks for all the advice on this work, NASPI!

Some necessary background – Transformer Vector Groups & Grounding

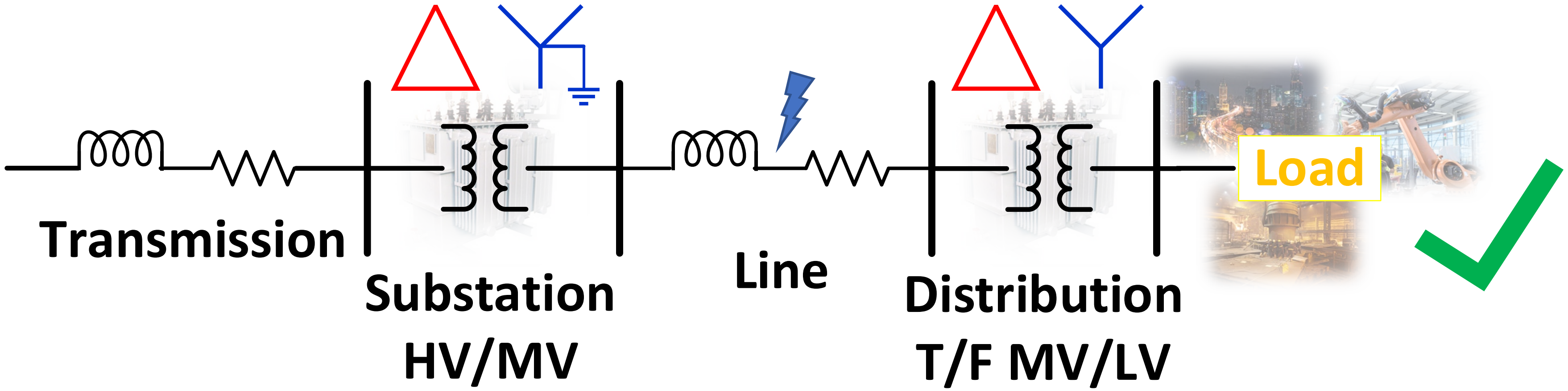
- Transformers (T/F) increase/decrease voltage levels by inducting power between a shorter coil (low side) and a longer coil (high side)
- 1-phase is simple, but 3-phase T/F is not:
  - 1-phase T/F = 1 coil on each T/F side (high & low)
  - 3-phase T/F = 3 coils on each T/F side
  - 3 coils/phases can be connected either in star or delta
  - The two 3-coiled T/F sides can change voltage phase
  - Star connection has a neutral that *could* be grounded





Distribution grid design with transformers

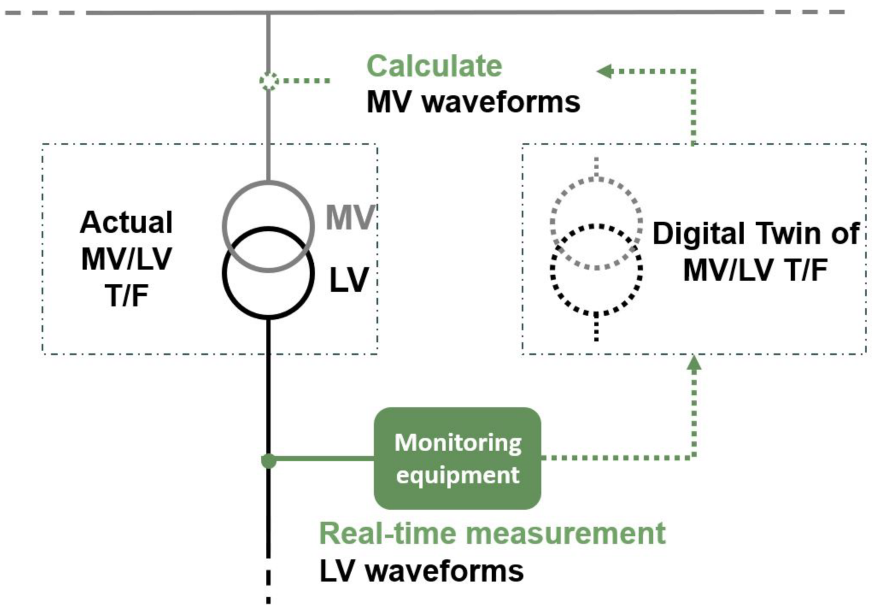
- Some 3-phase transformers (T/F) vector groups can operate at reduced capacity with one phase of one side at fault
- From circuit theory, a Delta-Star T/F with ungrounded neutral will not propagate line-ground (LG) and LLG faults from Delta to Star side
- A preferred Medium Voltage (MV) and LV architecture 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:
  - Low voltage (LV) is directly monitored
  - MV is estimated
  - Possibly monitor other concerns?
  - Minimum disruption compared to other methods



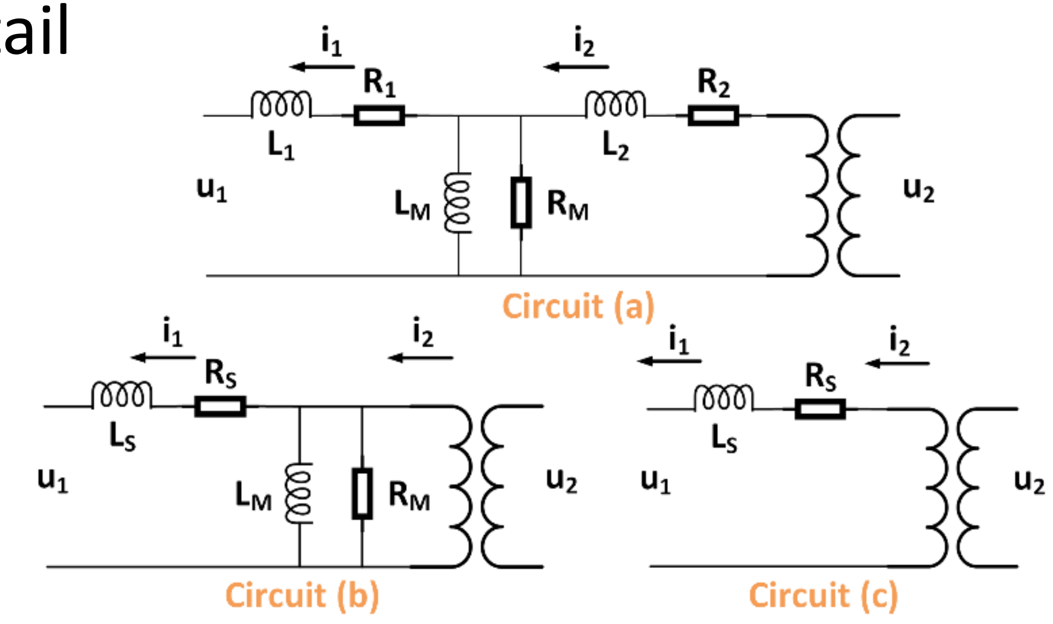
Thanks for all the advice on this work, NASPI!

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

$$\left.\begin{aligned} u_2(t) &= u'_1(t) + R_S i'_1(t) + L_S \frac{di'_1(t)}{dt} \\ i_2(t) &= \frac{u_2(t)}{R_M} + \frac{1}{L_M}\int u_2(t)\,dt + i'_1(t) \end{aligned}\right\} \Rightarrow$$

$$\left.\begin{aligned} u_2[n] &= u'_1[n] + R_S i'_1[n] + L_S(i'_1[n] - i'_1[n-1])f_s \\ i_2[n] &= \frac{u_2[n]}{R_M} + \frac{u_2[n] - u_2[n-1]}{L_M \cdot f_s} + i'_1[n] \end{aligned}\right\}$$



1: LV side, 2: MV side

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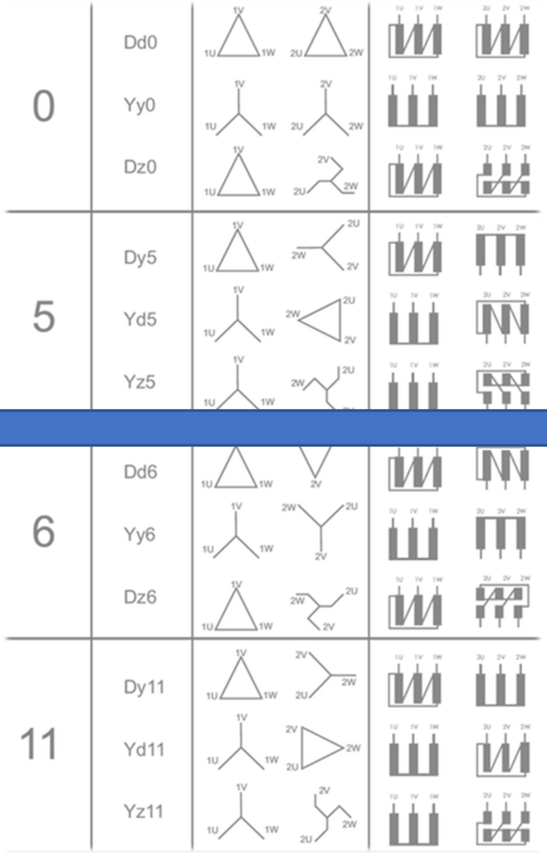
Thanks for all the advice on this work, NASPI!

Extending to the digital twin of 3-phase distribution transformers

$$\left.\begin{aligned} u_2[n] &= u'_1[n] + R_S i'_1[n] + L_S(i'_1[n] - i'_1[n-1])f_s \\ i_2[n] &= \frac{u_2[n]}{R_M} + \frac{u_2[n] - u_2[n-1]}{L_M \cdot f_s} + i'_1[n] \end{aligned}\right\}$$

One set for each phase



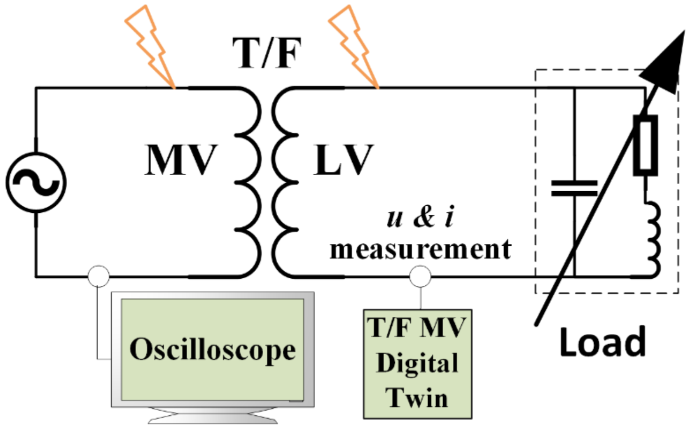
Yy0: $u_A = u_{2A}$ and $i_A = i_{2A}$

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

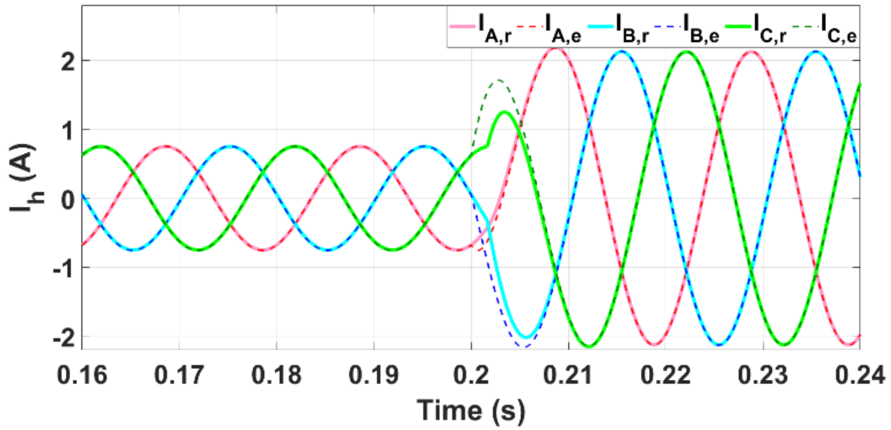
Dy11: $u_{AB} \cdot \sqrt{3} = u_{2A} - u_{2B}$ and $i_A = i_{2A} - i_{2B}$

Thanks for all the advice on this work, NASPI!

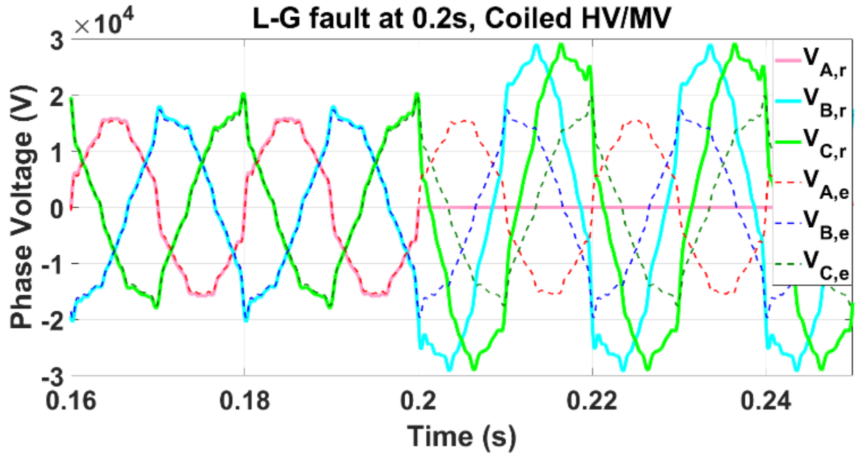
Testing the transformer (T/F) digital twin (1/2)



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



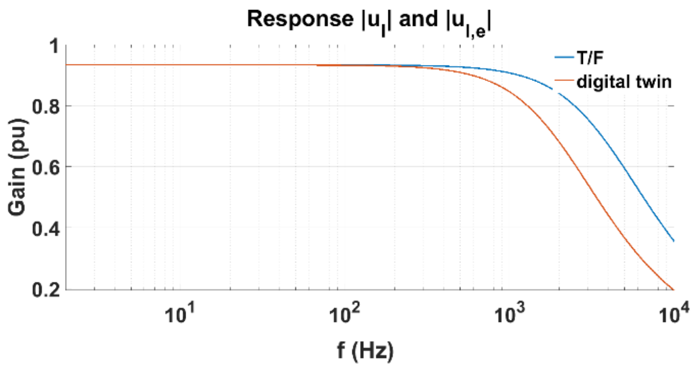
- All transient (but *very few)* properly captured:

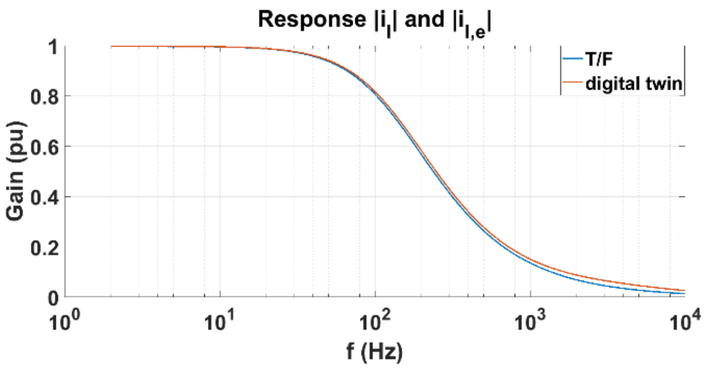


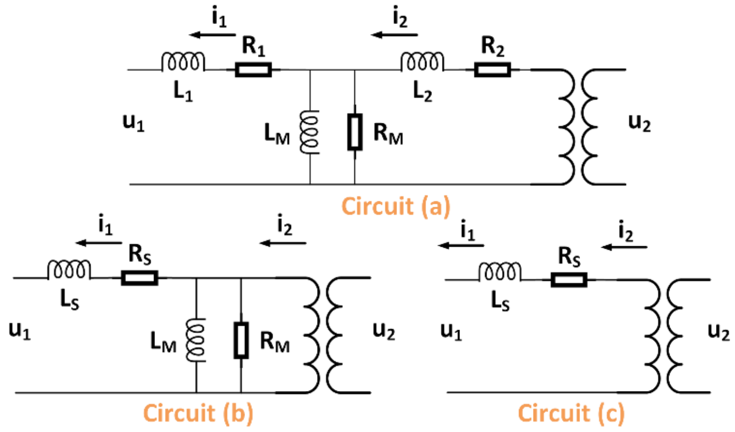
Thanks for all the advice on this work, NASPI!

Testing the transformer (T/F) digital twin (2/2)

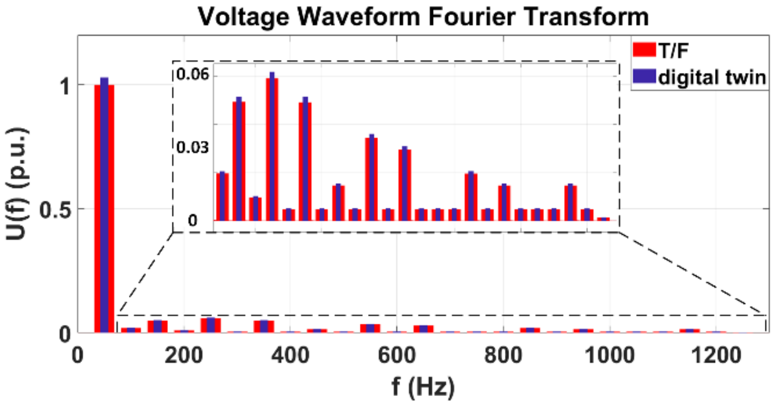
- Monitoring power quality – what are harmonics?
- The T/F circuit as a low-pass voltage filter







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



Publications & Funding

- **Moutis P**, Mousavi O. (2020). Digital Twin of Distribution Power Transformer for Real-Time Monitoring of Medium Voltage from Low Voltage Measurements. IEEE Transactions on Power Delivery (IEEE).

depsys

MARIE CURIE ACTIONS

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Thanks for all the advice on this work, NASPI!

Wildfire detection for non-preemptive disconnection of overhead lines

And keeping the lights on, under challenging circumstances…

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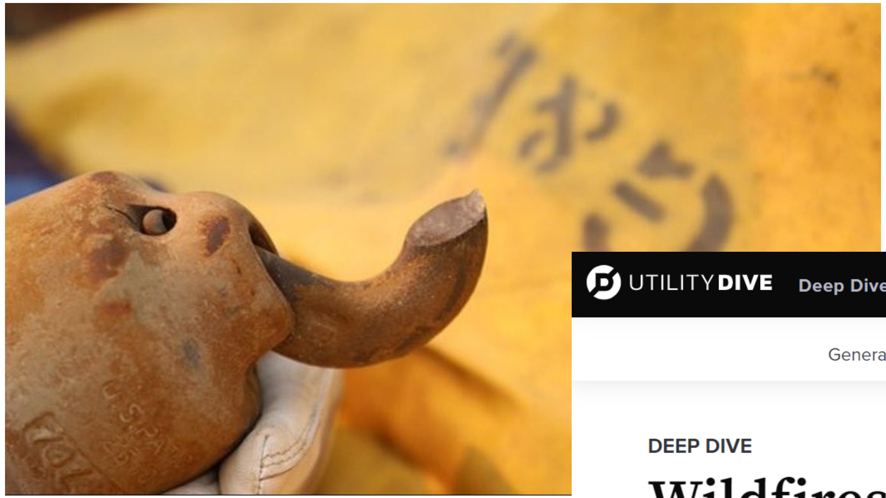
Thanks for all the advice on this work, NASPI!

Electricity stakeholders' role & response to fires



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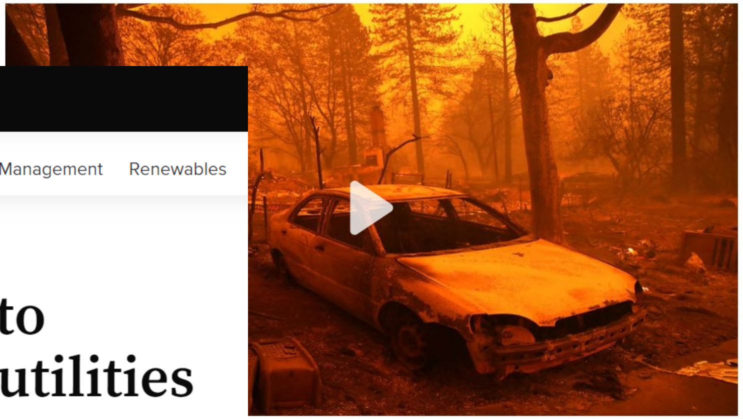
PG&E files for bankruptcy after California wildfires

By Rob McLean and Chris Isidore, CNN Business
Published 4:48 AM EST, Tue January 29, 2019



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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

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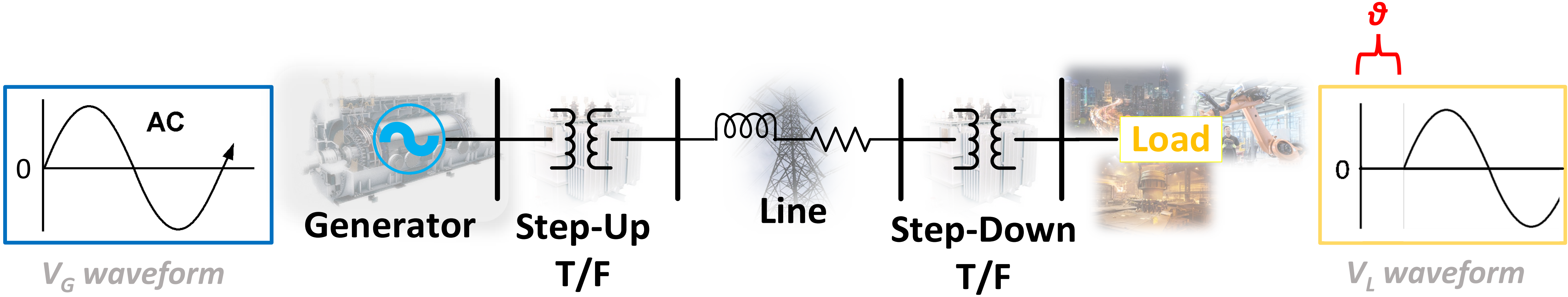
Thanks for all the advice on this work, NASPI!

Some Necessary Definitions – Active Power

- Energy (***E***) & Active Power (***P***)
  - Whatever moves, heats & charges
  - $P = \frac{\partial E}{\partial t}$
- Voltage Phase Angle (***ϑ***)
  - Measure of active power flow over a mostly inductive line (transmission)



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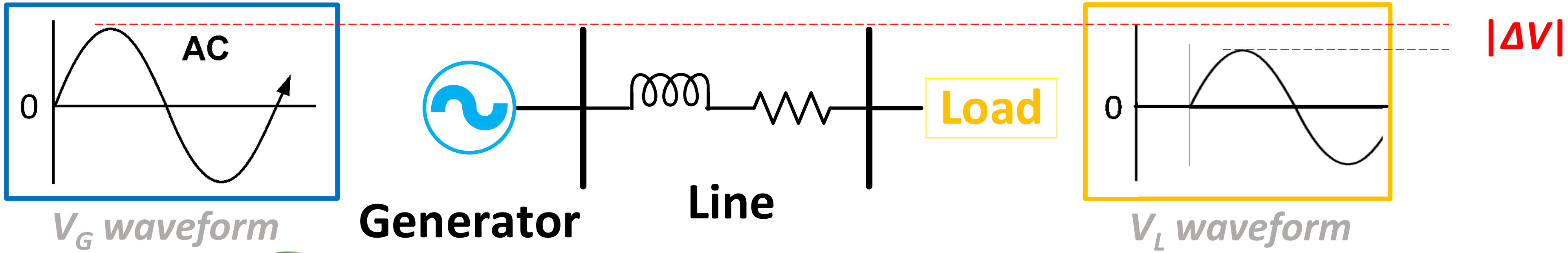
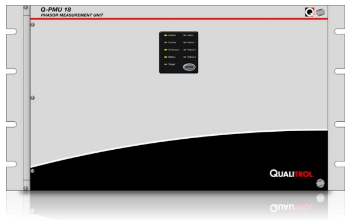
More Necessary Definitions – Reactive Power

- Why does voltage drop and, thus, causes concerns about its levels?
  - Ohm's law of drop of voltage over an impedance run by current
- I.e. because we transmit power over lines…
  - Transmission line reactance much greater than resistance
  - Resistance → line losses in ***P***, Reactance → line losses in reactive power ***Q***
- Voltage magnitude (**|*V*|**)
  - 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)



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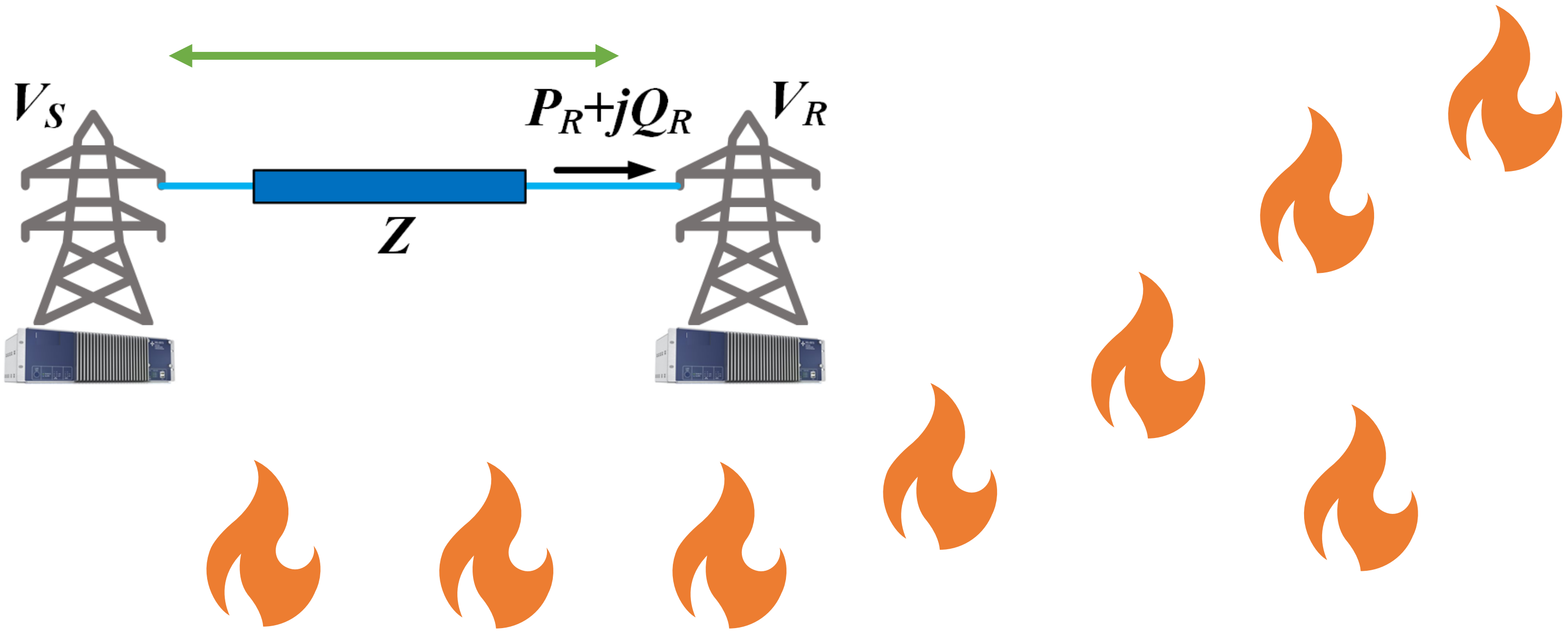
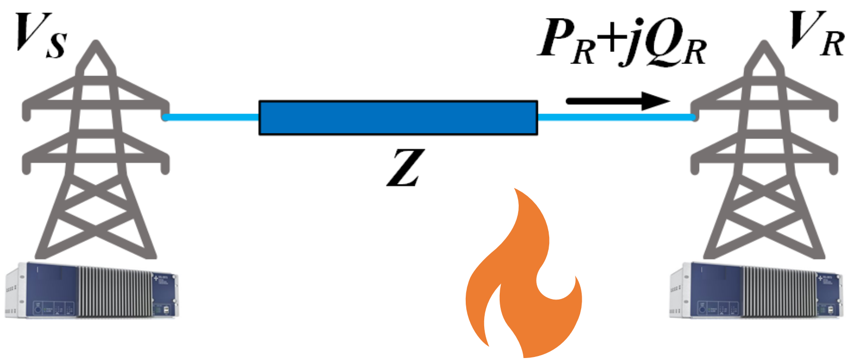
Non-preemptive disconnection of lines – Idea



Thanks for all the advice on this work, NASPI!

Impedance of a conductor

- Impedance includes resistance (affected by temperature) & reactance



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

Thanks for all the advice on this work, NASPI!

Relationship of Resistance to Ambient Temperature

- Particularly complicated
- But standardized
  - RI^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**

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

$$\frac{dT_c}{dt_T} = \frac{1}{m \cdot C_p}\left[R(T_c) \cdot I^2 + q_s - q_c(V_w, T_s, T_a,) - q_r(T_s, T_a)\right]$$

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Thanks for all the advice on this work, NASPI!

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

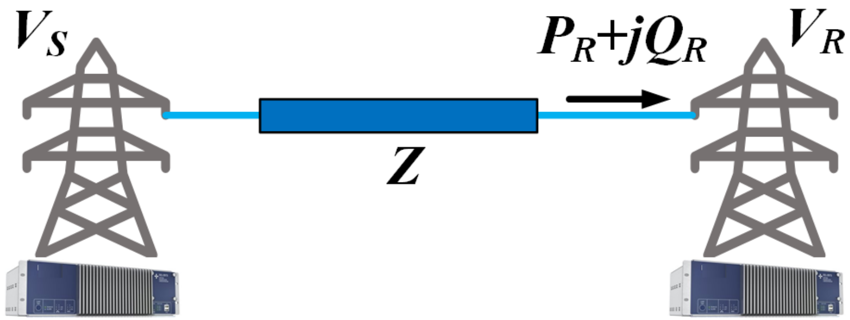
TEMPERATURE CHANGE AT DISTANCE d FROM AN OVERHEAD LINE FOR HEATING TIME t_F

t_F (s)	d (m)	ΔT_a (°K or °C)	t_F (s)	d (m)	ΔT_a (°K or °C)
10	50	$8.23 \cdot 10^{-5}$	10	5	30.99
30		$1.42 \cdot 10^{-4}$	30		53.69
60		$2.02 \cdot 10^{-4}$	60		75.93
10	10	5.81	10	1	71.61
30		10.06	30		124.03
60		14.23	60		175.40

Method of detecting approaching forest fire through line impedance

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

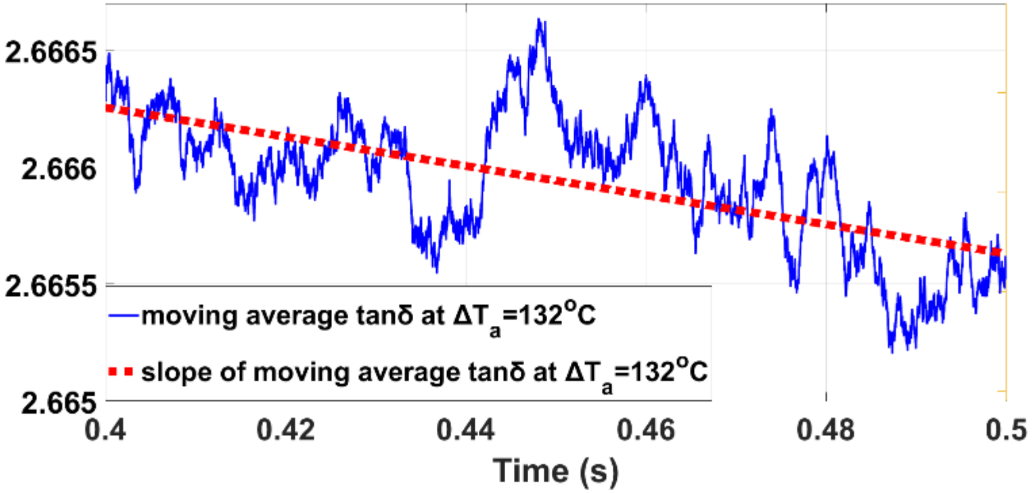
- It is $\tan(\delta(T_c)) = \frac{X}{R(T_c)}$

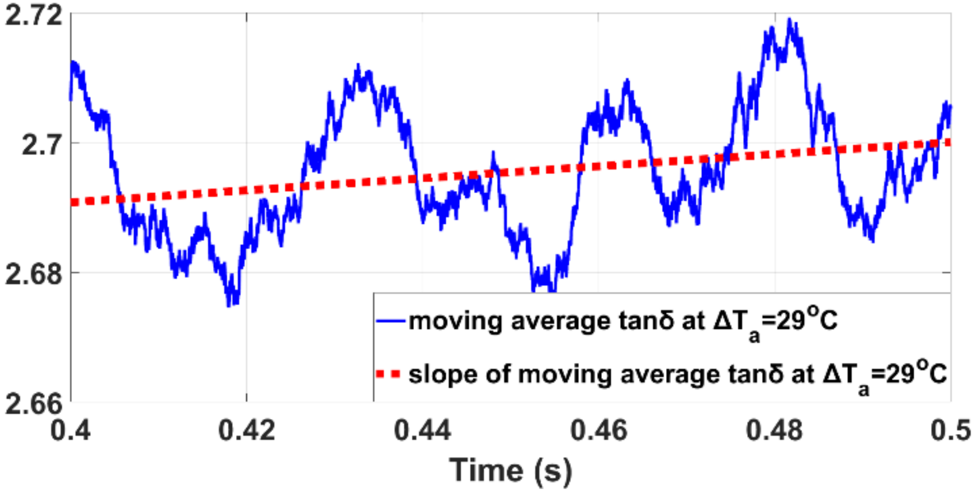


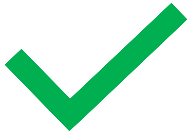
- tan(δ) may be estimated from electrical measurements as:

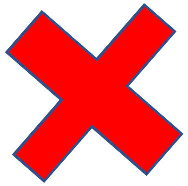
$$tan\delta = \frac{P_R V_S sin\theta + Q_R V_S cos\theta - Q_R V_R}{P_R V_S cos\theta - Q_R V_S sin\theta - P_R V_R}$$

How should the method operate – and not…









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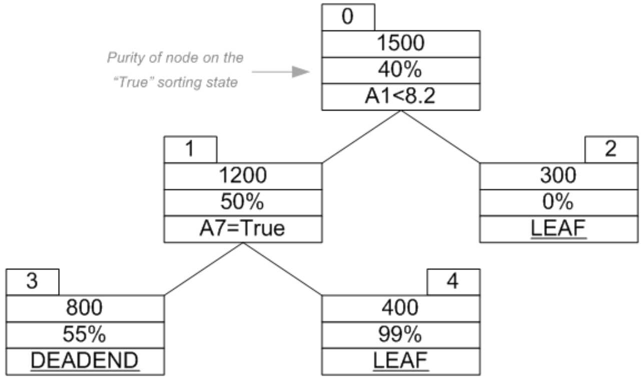
Extensive statistical testing to assess

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 ΔT_a between 0-225.5 ^{o}C (including no fire),
2. Ambient temperature T_a ahead of the effect of the fire between 10-40 ^{o}C,
3. Wind speed V_w between 0-6.5 m/s,
4. Conductor surface temperature T_s between 10-100 ^{o}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)



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Thanks for all the advice on this work, NASPI!

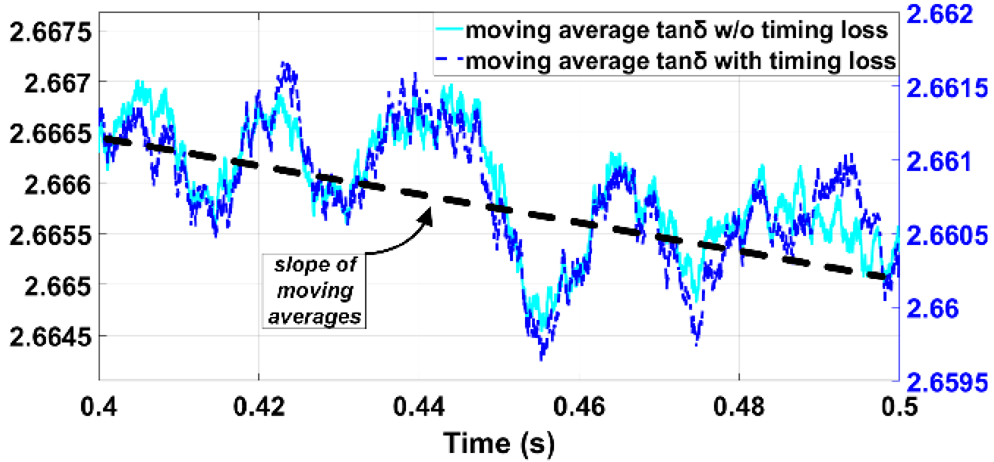
Control Parametrization & Conditions of Detection – *In Silico*

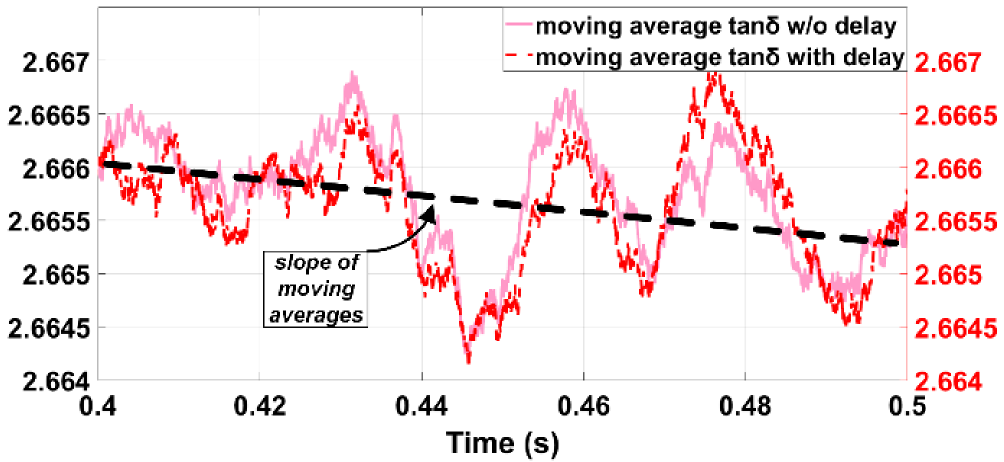
- Control parametrization capturing fire approach in 0.1 s
- Conditions to capture fire approach from decision tree inference:
  - 86% of the cases with fire burning for at least 60 s at a distance of at most 5 m from the conductor,
  - 100% of the cases with V_w<1.35m/s and line loading >90% and
  - 94% of the cases with T_s<57°C, 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.

Thanks for all the advice on this work, NASPI!

Performance (False Positives, Timing Loss & Delay, Capacitor Switching) – *In Silico*

Control type & conditions	$\Delta tan\delta_t$ performance (%)			
	TP	TN	FP	FN
Control 1 with ΔT_c>2.87°C	99.32	0.29	0.29	0.10
Control 2 with ΔT_c>2.87°C and V_{err}<0.003%	89.13	0.00	0.00	10.87





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Thanks for all the advice on this work, NASPI!

Publications

- **Moutis P.,** Sriram U. (2022). PMU-Driven Non-Preemptive Disconnection of Overhead Lines at the Approach or Break-Out of Forest Fires. IEEE Transactions on Power Systems.

Conclusions & Path Forward

Thanks for all
the advice on
this work, NASPI!

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

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Thanks for your attention!

Questions, please?

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