Digital Twins for Real-Time Monitoring of Inverter Dominated Grids

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Introductions

- What keeps me up at night?

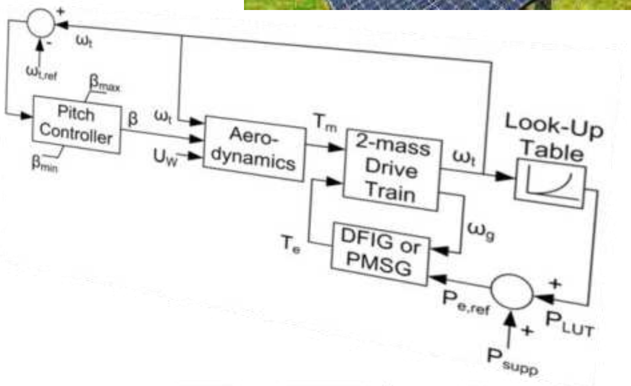
  Wide integration & *seamless* operation of (volatile) renewables in electrical grids

- 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



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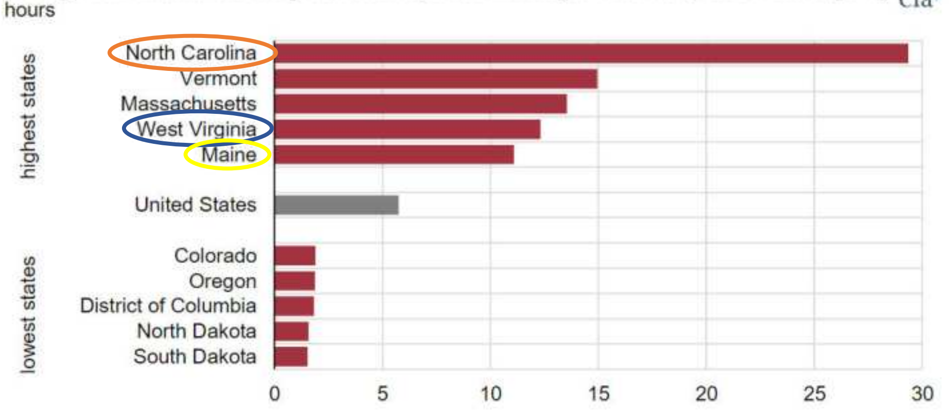
Outline

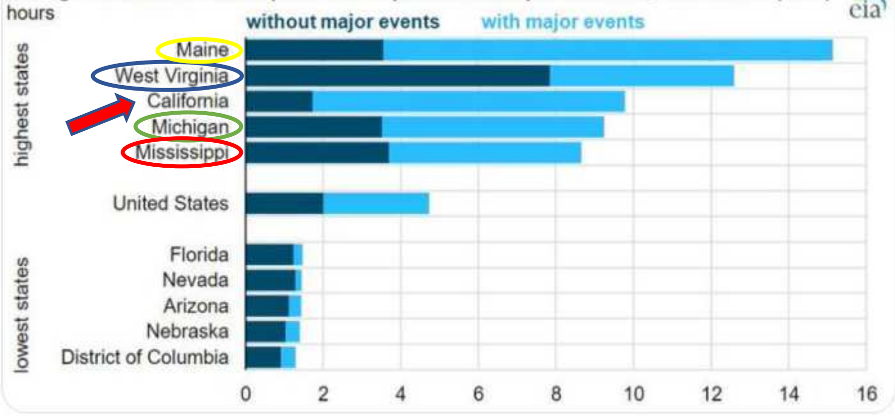
- *Introduction:* Motivation for Real-Time Monitoring
- *Part 1:*
  Digital Twin of Distribution Transformer
- *Part 2:*
  Wildfire detection with the Digital Twin of Overhead Conductor
- *Conclusion & Path Forward*

The Electrical Grid is ***not*** OK & ***not*** fair…

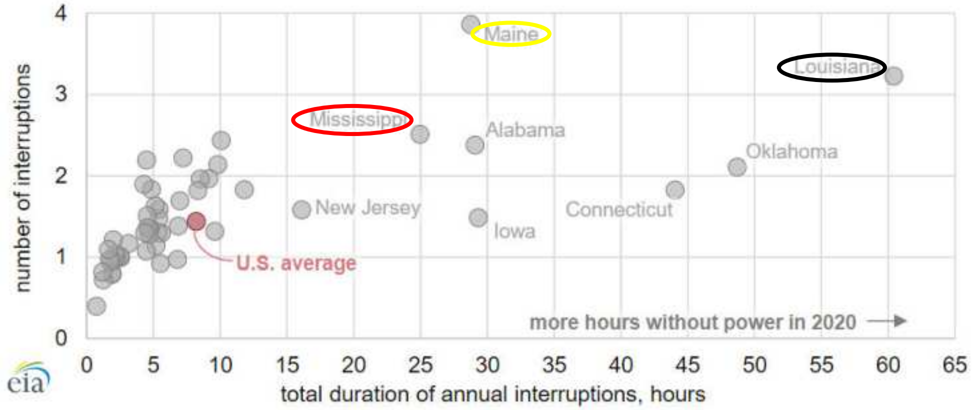
Average total annual electric power interruption duration per customer, select states (2018)



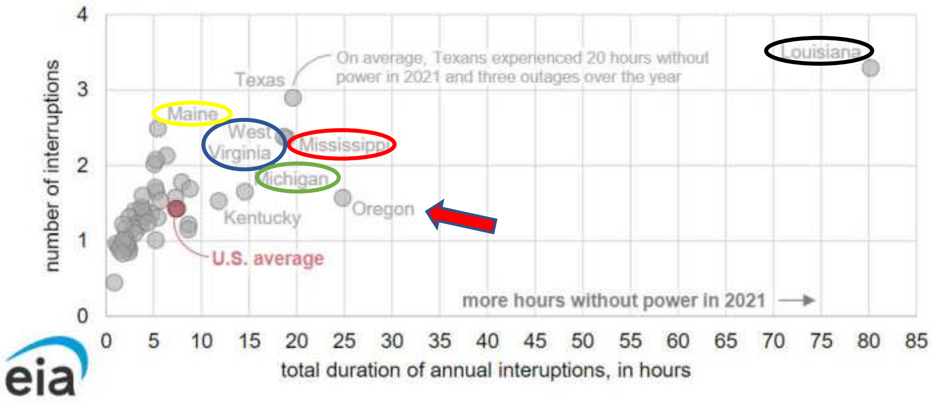
Average total annual electric power interruption duration per customer, select states (2019)



Average total annual electric power interruption duration and frequency per customer, by U.S. state (2020)



Average total annual electric power interruption duration and frequency per customer, by U.S. state (2021)



Rank	STATE	Household Income (increasing)
1	MISSISSIPPI	$57,148
2	WEST VIRGINIA	$58,126
3	NEW MEXICO	$60,728
4	LOUISIANA	$61,042
5	ARKANSAS	$61,212
6	KENTUCKY	$61,790
7	ALABAMA	$63,401
8	OKLAHOMA	$66,786
9	TENNESSEE	$66,989
10	SOUTH CAROLINA	$67,922
11	IDAHO	$68,818
12	INDIANA	$69,505
13	MISSOURI	$69,614
14	FLORIDA	$69,884
15	NORTH CAROLINA	$70,000
16	MICHIGAN	$70,163
17	OHIO	$70,209
18	GEORGIA	$71,504
19	MONTANA	$71,836
20	MAINE	$72,988
21	NEVADA	$73,083
22	ARIZONA	$73,262
23	TEXAS	$74,636
24	PENNSYLVANIA	$74,805
25	SOUTH DAKOTA	$74,820

2022 US Census Bureau Median Family Income

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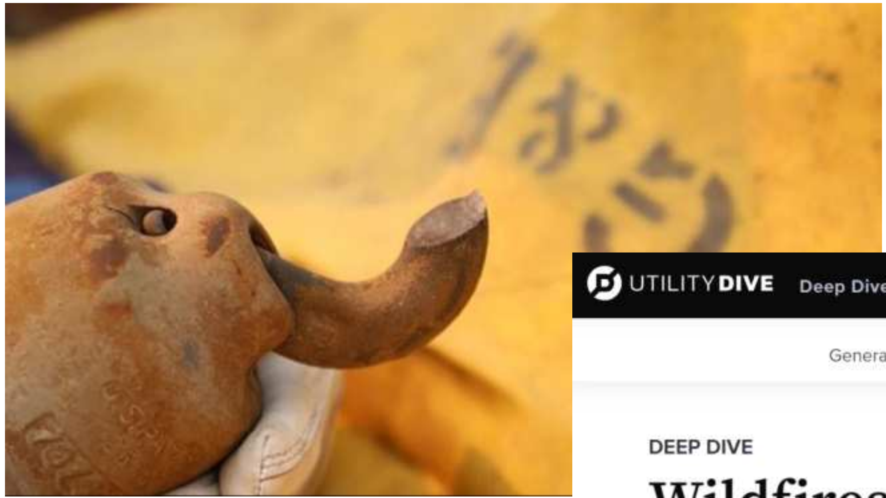
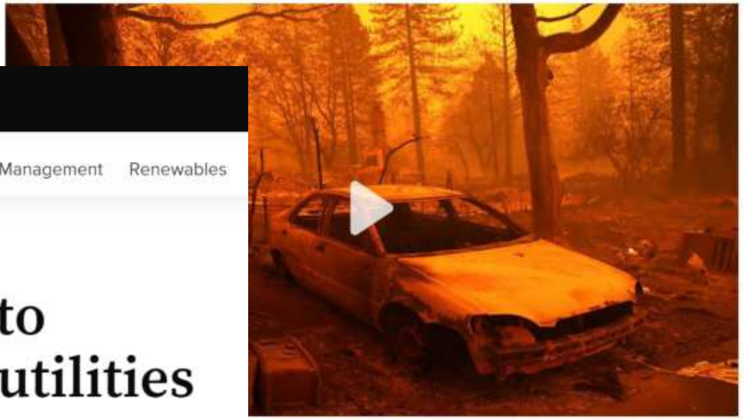
Electricity stakeholders’ role & response to fires



CNN BUSINESS Markets Tech Media Success Perspectives Videos

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



UTILITY DIVE Deep Dive Opinion Podcasts Library Events

Generation T&D Grid Reliability Electrification Load Management Renewables

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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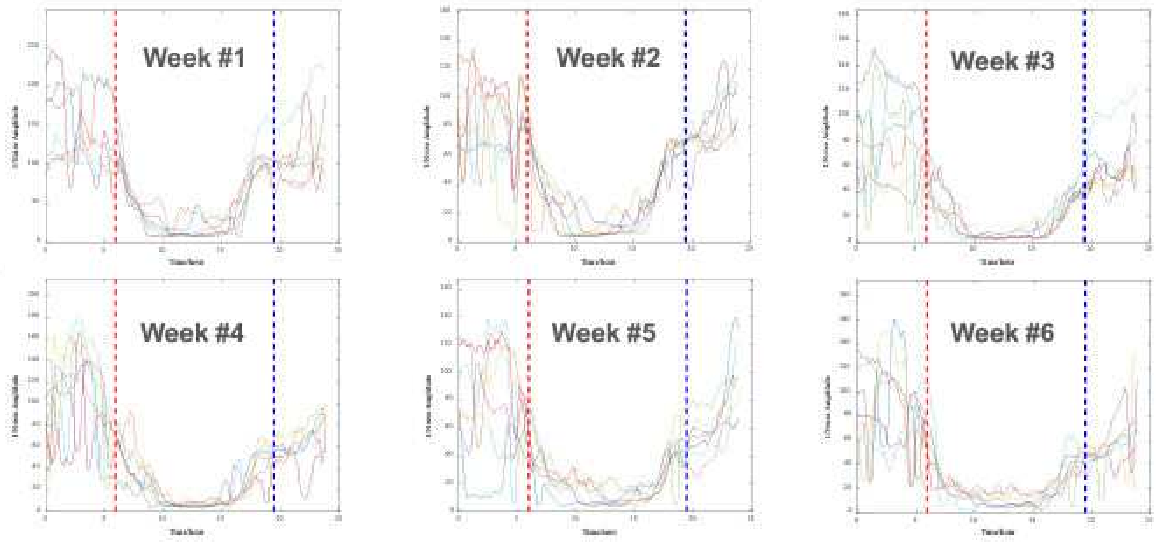
Grid phenomena become faster as grid inertia is displaced

‘relative inertia’ results from one island

------ Local sunrise time

------- Local sunset time



Work funded by

DOE SETO project led by NREL

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Data & Test Support: TVA, DOM, KIUC, PGE, AES, GPTech, NERC

National Renewable Energy Laboratory

The University of Tennessee Knoxville

Oak Ridge National Laboratory

GPTech aes PG&E Kaua‘i Island Utility Cooperative TVA Dominion Energy

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What does the grid look like?..

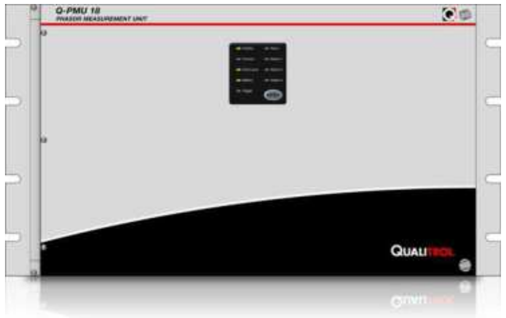
- Designed to operate under (some) faulty conditions
  - Fault, ageing and poor maintenance go unnoticed until effects/faults pile up
- Renewables arbitrarily installed & (mostly) passively operated
- Numerous control and pain points
- Faster propagation of electromechanical phenomena

Necessary to monitor in real-time <u>AND</u>
enable local/decoupled decision making

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

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 (IEEE/IEC 60255-118-1-2018)

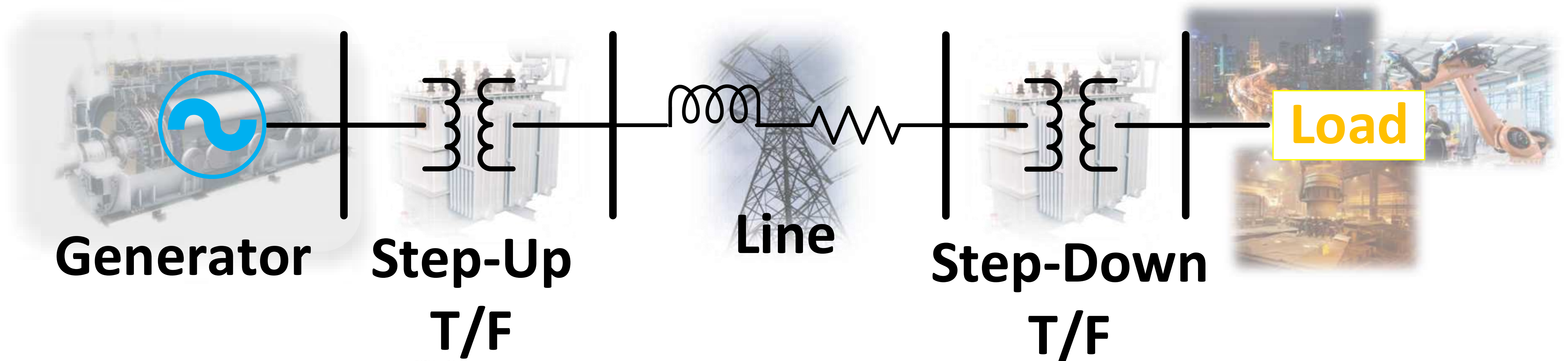


Digital Twin of Distribution Transformer

Real Time Fault and Power Quality Monitoring

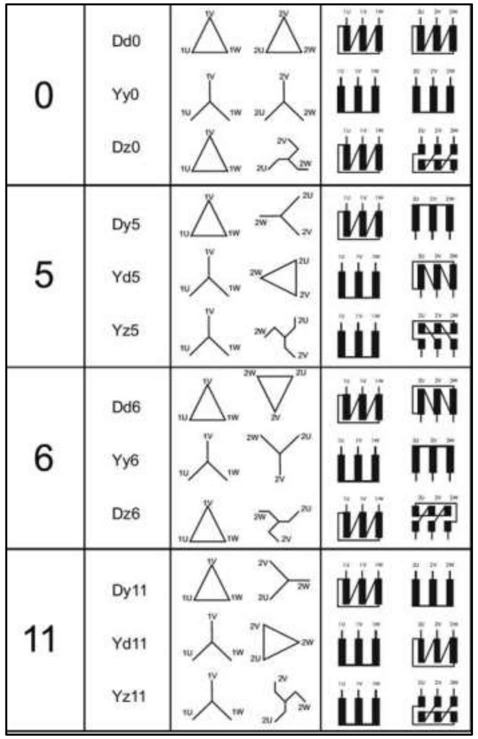
Some necessary background – Grid Design

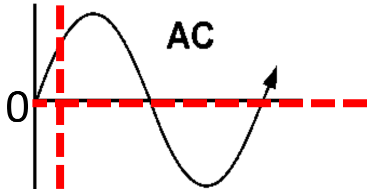
- AC power travels long with fewer losses at higher voltage
- Most typical devices, motors and generators barely operate at medium voltage (size, protection, etc)



Some necessary background – Transformer Vector Groups & Grounding

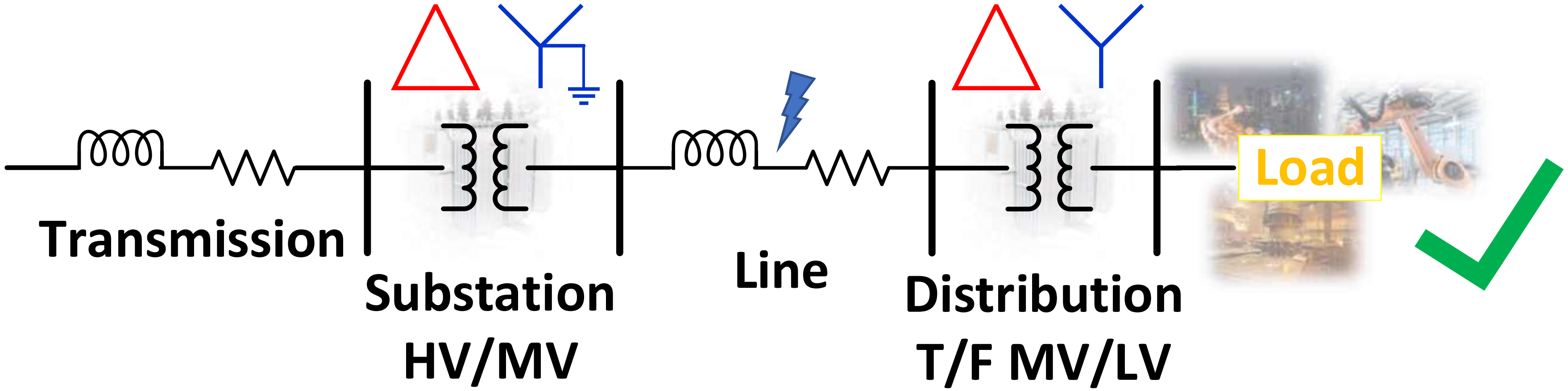
- Transformers (T/F) increase/decrease voltage levels by inducting power between a shorter coil (low side) and a longer coil (high side)
- 1-phase is simple, but 3-phase T/F is not:
  - 1-phase T/F = 1 coil on each T/F side (high & low)
  - 3-phase T/F = 3 coils on each T/F side
  - 3 coils/phases can 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

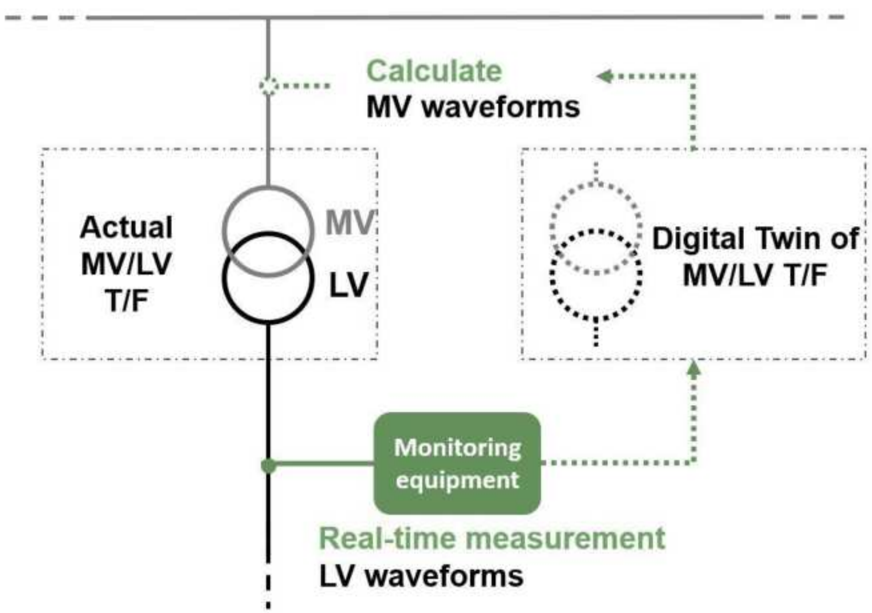
- Some 3-phase transformers (T/F) vector groups can operate at reduced capacity with one phase of one side at fault
- From circuit theory, a Delta-Star T/F with ungrounded neutral will <u>not</u> propagate line-ground (LG) and LLG faults from Delta to Star side
- A preferred Medium Voltage (MV) and LV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

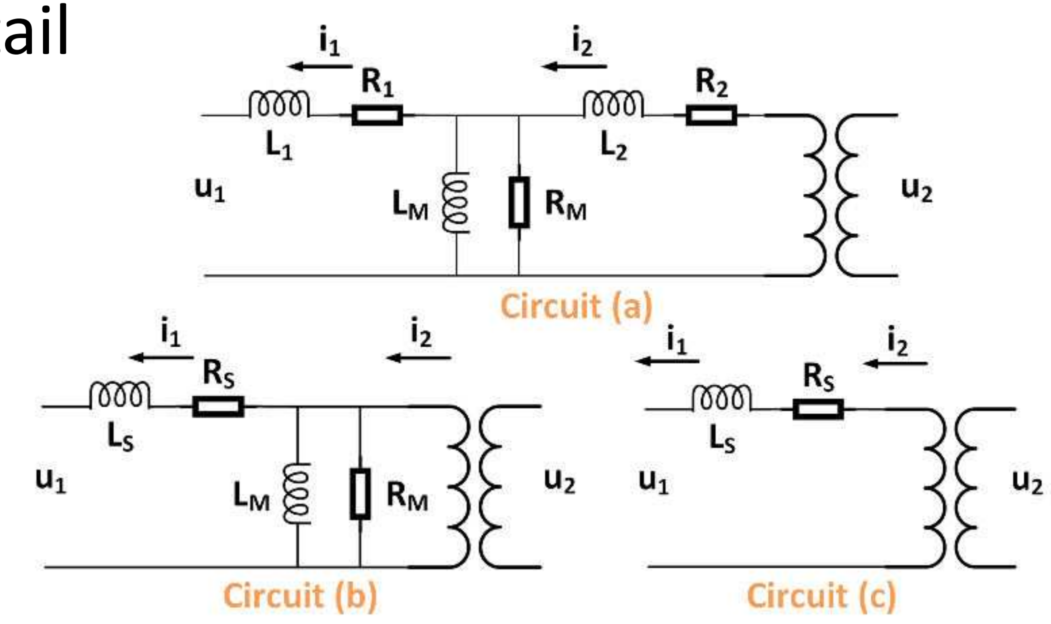


Defining the digital twin of a single-phase distribution transformer (T/F)

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

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

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

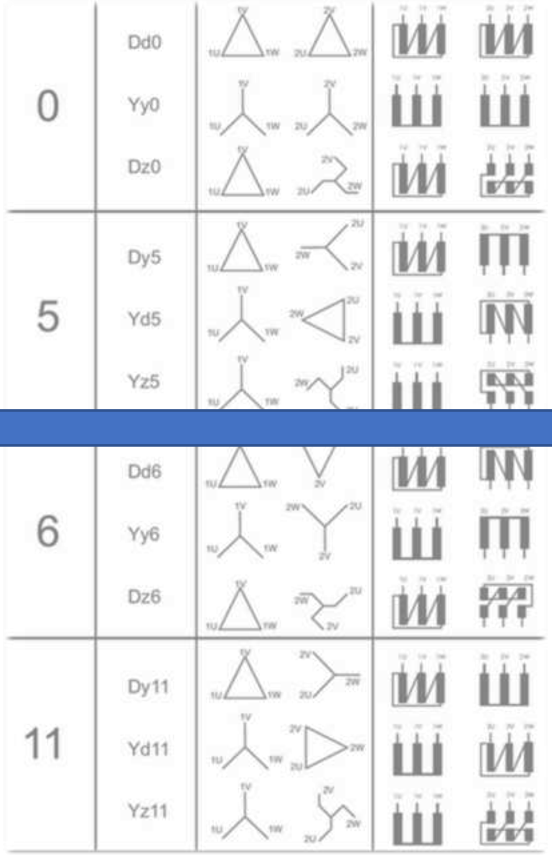


1: LV side, 2: MV side

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

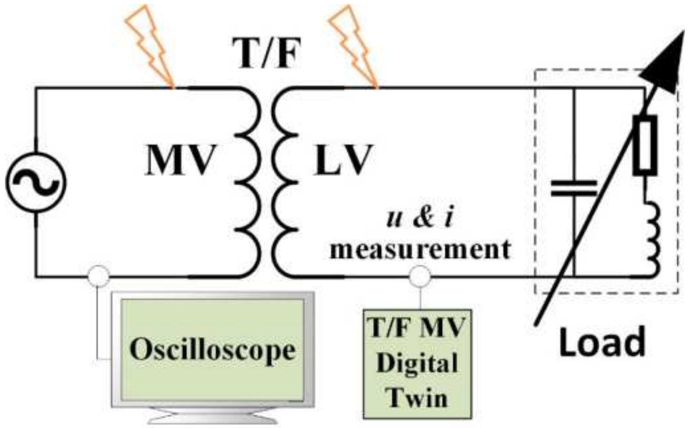


Yy0: $u_A = u_{2A}$ and $i_A = i_{2A}$

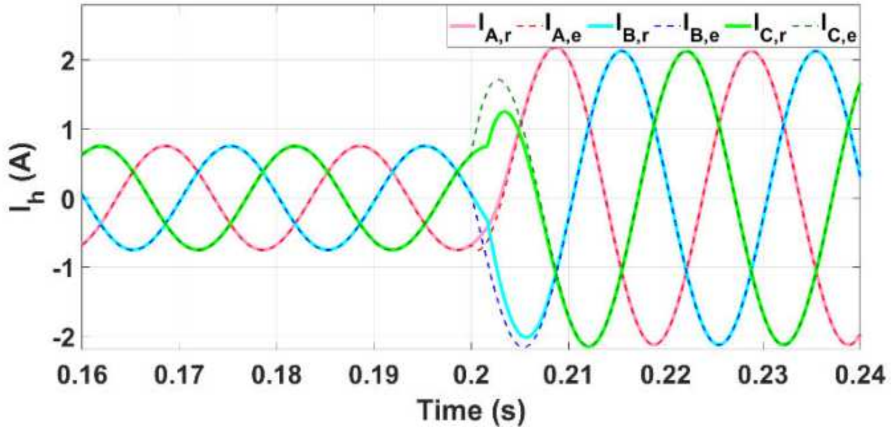
Dy1: $u_{AB} \cdot \sqrt{3} = u_{2A} - u_{2C}$ and $i_A = i_{2A} - i_{2C}$

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

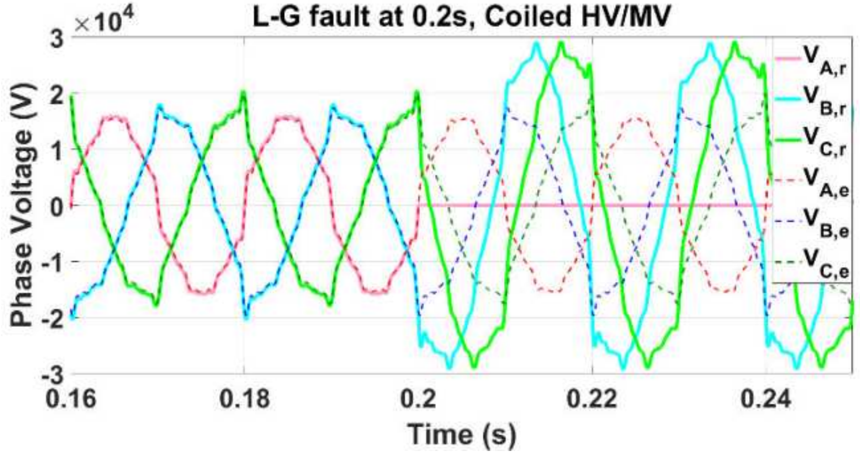
Testing the transformer (T/F) digital twin (1/2)



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

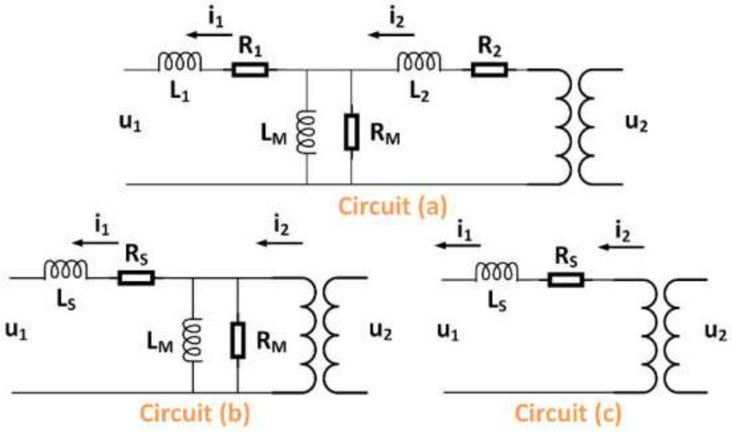


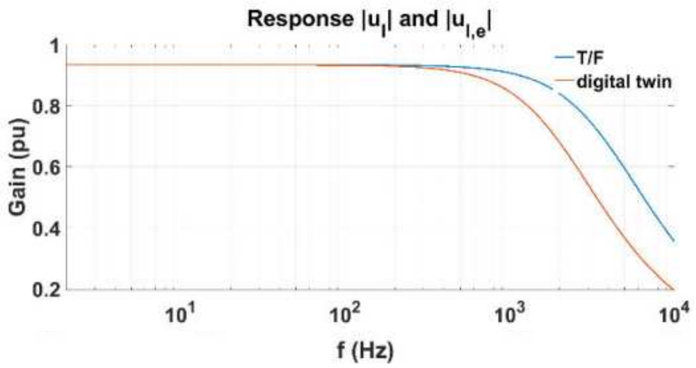
- All transient (but *very few)* properly captured:

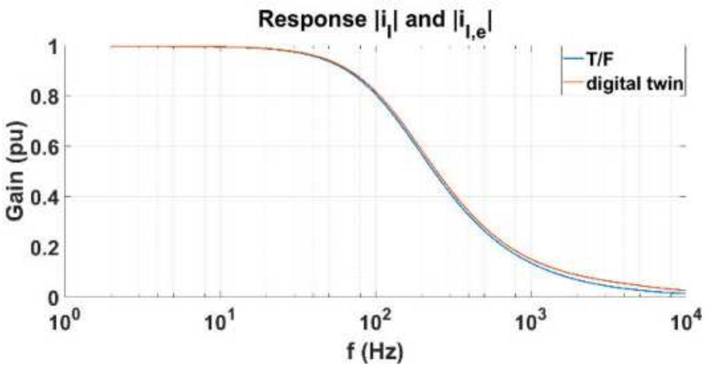


Testing the transformer (T/F) digital twin (2/2)

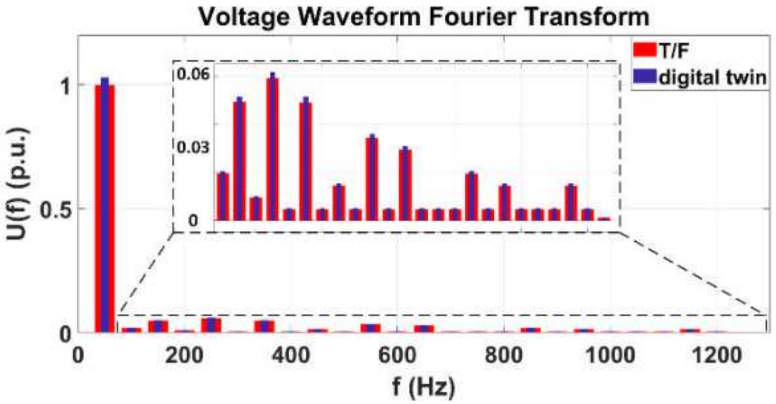
- Monitoring power quality – what are harmonics?
- The T/F circuit as a low-pass voltage filter







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



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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).

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Wildfire detection for non-preemptive disconnection of overhead lines

And keeping the lights on, under challenging circumstances…

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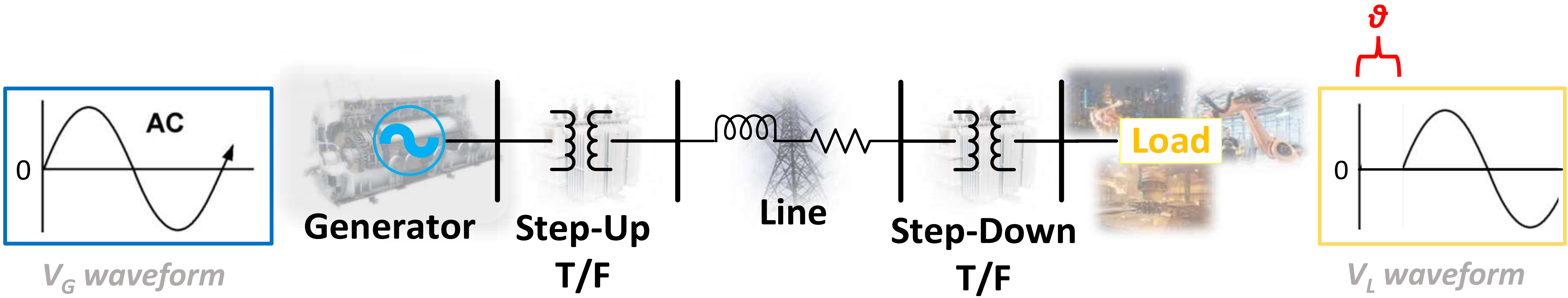
Some Necessary Definitions – Active Power

- 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)



V_G *waveform*

V_L *waveform*

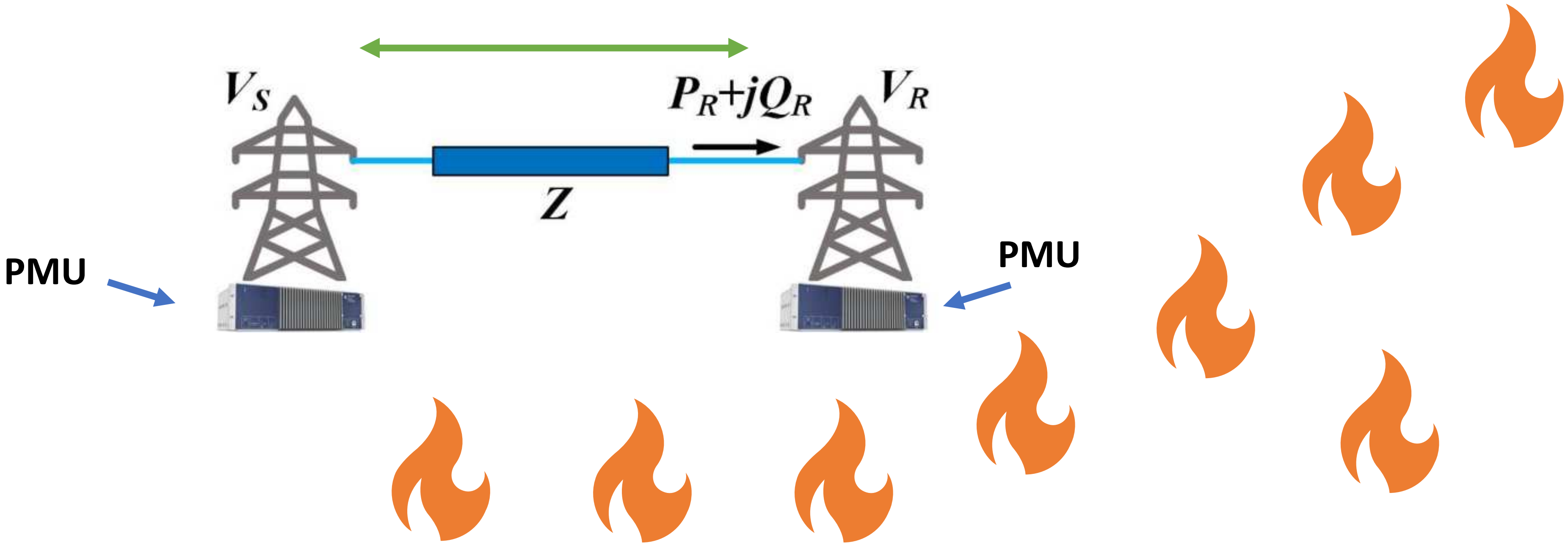
More Necessary Definitions – Reactive Power *Q*

- 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 <u>mostly by the line induction</u> (transmission)

V_G *waveform*

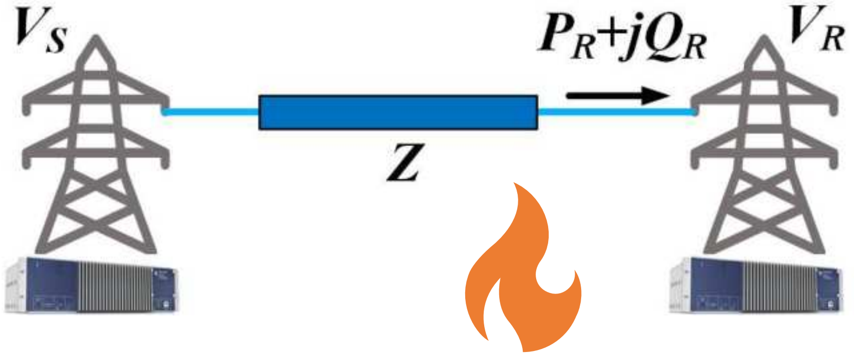
V_L *waveform*

Non-preemptive disconnection of lines – Idea



Impedance of a conductor

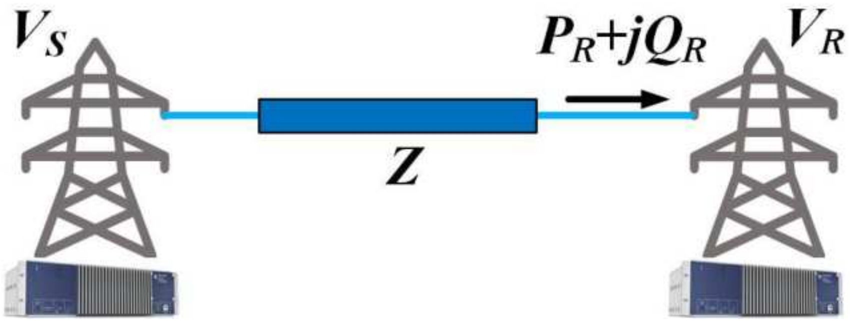
- Impedance includes resistance (affected by temperature) & reactance



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

Method of detecting approaching forest fire through line impedance

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



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

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

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
  - V_w wind speed cooling
  - 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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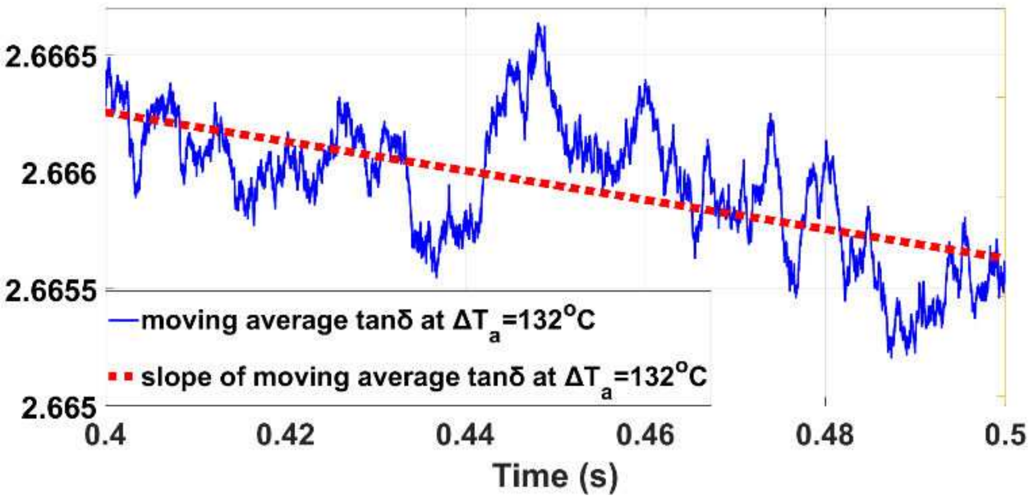
Effect of fire to ambient temperature

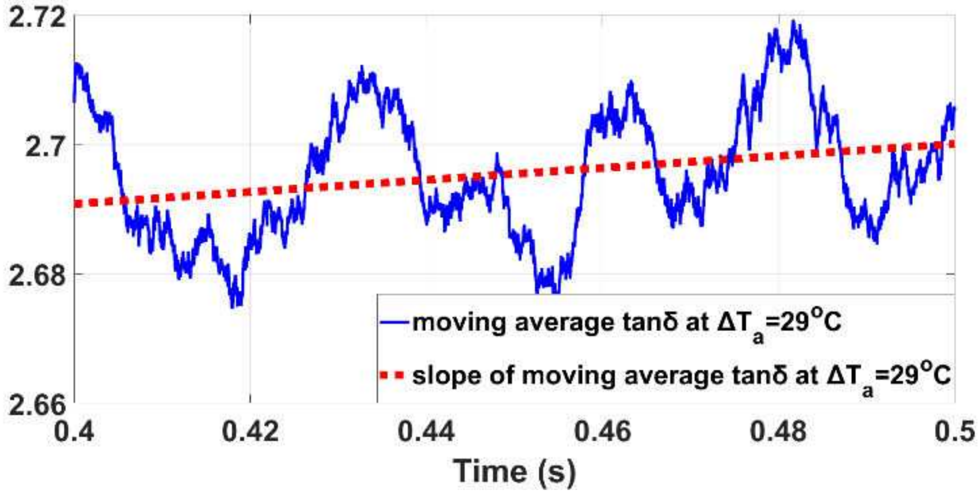
- Non-trivial relationship
- Function of fuel of fire, distance from a point of measurement and duration of the fire at a given intensity
- For a moss pine forest with several trees

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

How should the method operate – and not...





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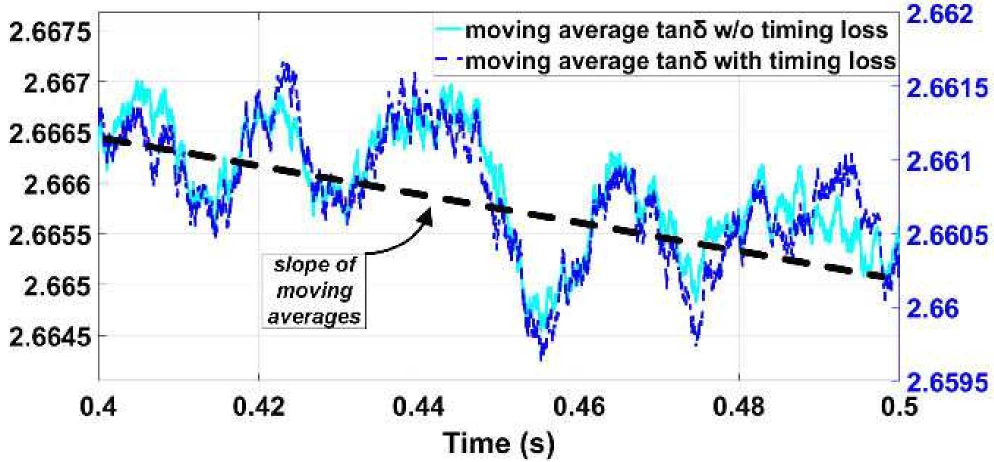
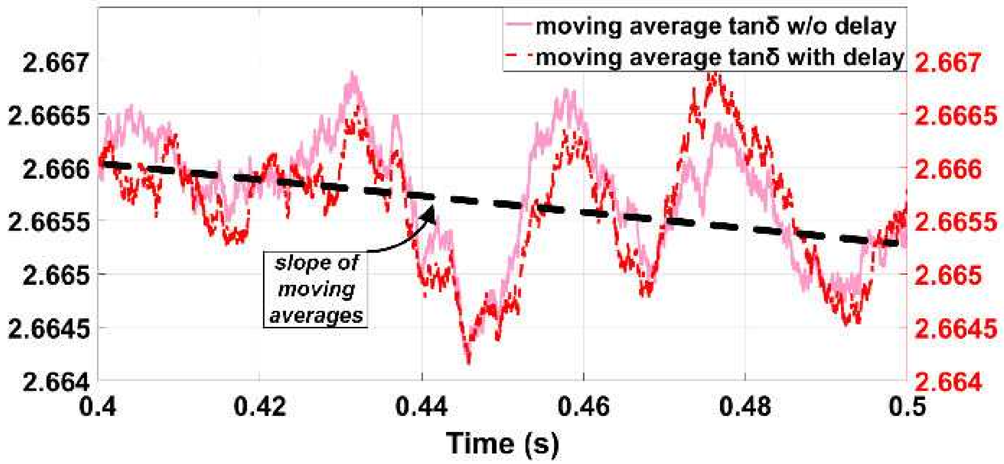
Performance (False Positives, Timing Loss & Delay, Capacitor Switching) – *In Silico*

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



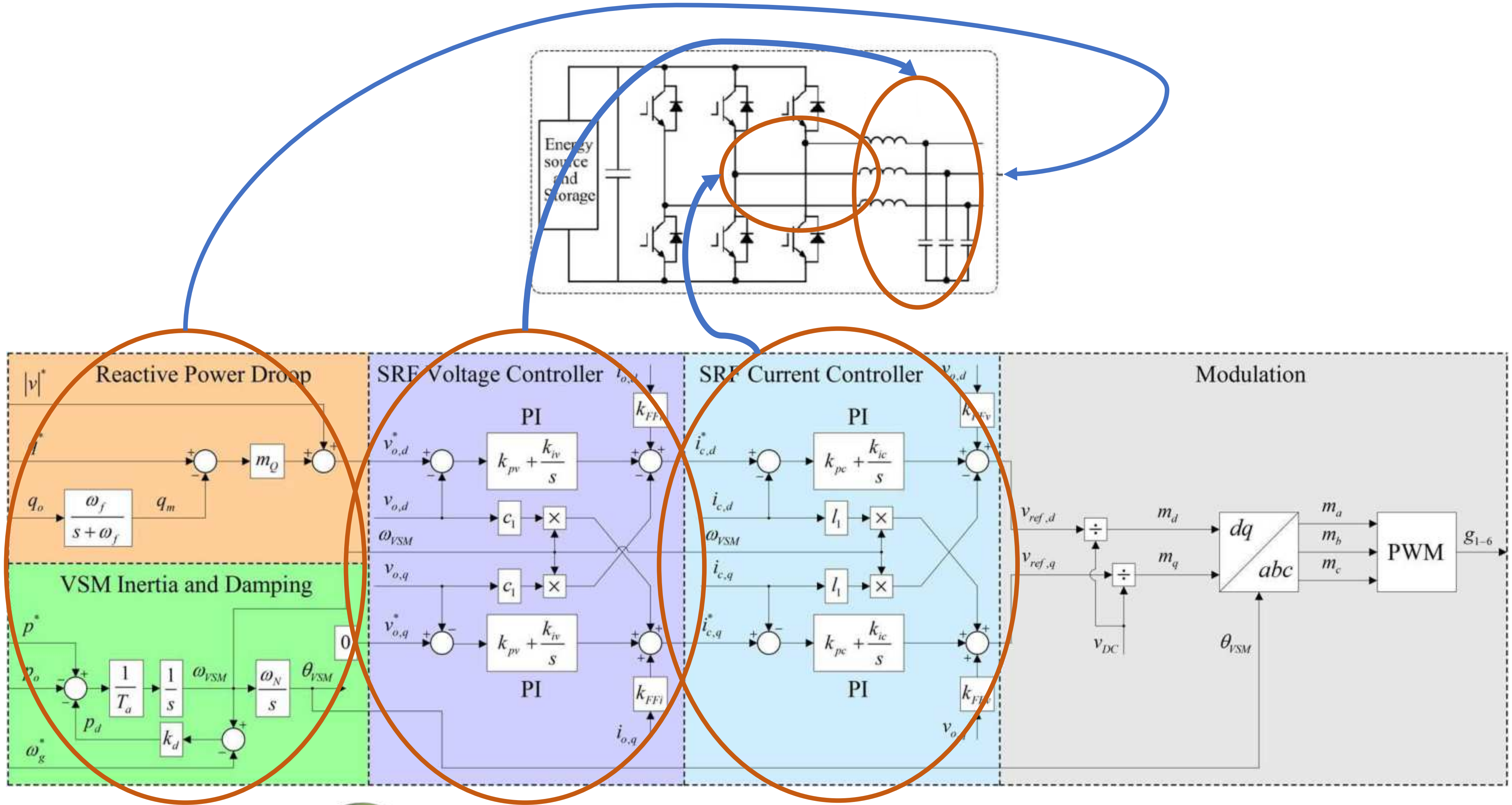


Publications

- **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.

Towards Inverter Digital Twinning

Typical Grid Forming Inverter Topology & Control



Grid Stability & Security with Inverters

- All controllers of an inverter may cause instability => demanding tuning
- Most owner-provided inverter models are invalid => operator uncertainty
- Emulating conventional generation improves stability & security => affects inverter characteristics & requires additional components
- Grid impedance affects inverter control parametrization => coordinated control & real-time grid impedance monitoring necessary
- Weakened inertia accelerates propagation of instability => operators' response times limited over countless control points

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Conclusions & Path Forward

- (Near-) Real-time Monitoring & ‘decoupled’ automation becomes necessary across the grid from transmission to distribution
- Digital twinning “passive” components (T/F, lines, etc) easier
- Digital Twinning inverter based resources much more elaborate

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