Synchronized Waveforms
– A Frontier of Data-Based Power System and Apparatus Monitoring, Protection, and Control

Visionary Paper Series
IEEE Transactions on Power Delivery

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About T-PWRD and Its Visionary Paper Series

IEEE Trans. on Power Delivery (T-PWRD)

- A PES journal that publishes the most industry relevant, application oriented papers
- Its scope also covers research work leading to industry standards
- It published most of the early research on the applications of precision time including phasor measurements

T-PWRD visionary paper series

A new platform for seasoned researchers and technical committees

- To share their visions on a significant trend or challenge facing power industry,
- To present innovative concepts that may produce a wide range of impacts,
- To promote, influence or lead the research activities in an area

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- Submit a 2~3 page proposal on your visions to PWRD EIC at any time
- The proposal will be screened by EIC and then by two experts
- Decision and feedback is provided to authors. If the decision is YES
- Authors submit a full paper in 6 months using the paper type “Visionary series”
- The paper is reviewed just like other papers but expert reviewers are used
- Accepted work will be publicized using PES webinar in addition to publication in PWRD

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Sharing your vision

PWRD editorial board welcomes your submissions to the Visionary Paper Series so that your visions and leadership can be made known to worldwide power engineering community

In today's webinar, Prof. Wilsun Xu will share his visions on the potentials of synchronized waveform data

Synchronized Waveforms
– A Frontier of Data-Based Power System and Apparatus Monitoring, Protection, and Control*

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Outline:

1. Status of synchronized waveform (sync-wave) data
2. Characteristics of the data and example applications
3. Vision 1 - Platforms for sync-wave applications
4. Vision 2 - Strategies for application development
5. Sync-wave data versus synchrophasor data
6. Conclusions & main takeaways

1. Status of sync-wave data

Defining synchronized waveform (sync-wave) data – three characteristics:

- Voltage or current waveform data (sampled at least 64 samples/cycle, or 3.8kHz),
- With (explicit or implicit) precision time information for the data samples,
- The information is sufficient to align waveforms recorded at multiple locations to an acceptable accuracy (to be established by a standard).

Example of sync-wave data

Hour	Minute	Second	Loc 1 Volt
23	5	0.000001	-109.63
23	5	0.000066	-113.68
23	5	0.000132	-117.47
23	5	0.000197	-120.35
23	5	0.000262	-122.78
23	5	0.000327	-125.24
23	5	0.000392	-127.44
23	5	0.000457	-129.19
23	5	0.000522	-130.97

Hour	Minute	Second	Loc 2 Volt
23	5	0.000217	100.12
23	5	0.000282	103.45
23	5	0.000347	106.88
23	5	0.000412	109.44
23	5	0.000478	111.64
23	5	0.000543	113.62
23	5	0.000608	115.62
23	5	0.000673	117.50
23	5	0.000738	119.54

- 256 samples/cycle, i.e. 15.9kHz sampling rate
- 1μSecond GPS timestamp accuracy

You can get this and other data from the PES PQ Data Analytics WG website: https://grouper.ieee.org/groups/td/pq/data/

1. Status of sync-wave data

Devices with sync-wave measurement capabilities (SMU) are already available

Portable PQ monitor

Stationary PQ monitor

Gapless SMU

Relay-based SMU

Merging Unit

Three industry trends driving the need for waveform data:

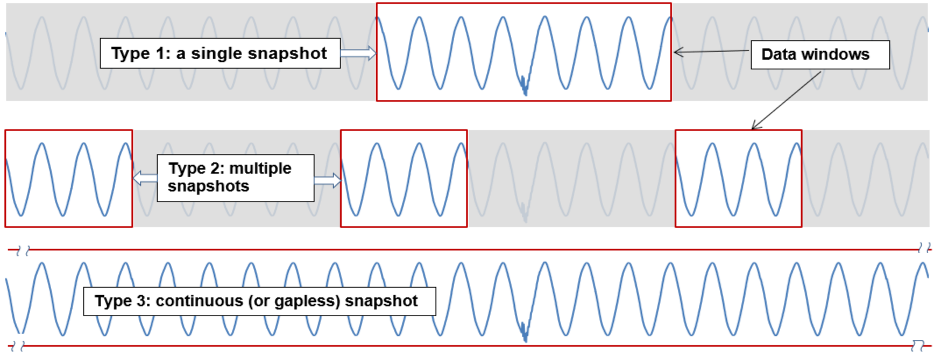
- Increased adoption of power electronic (PE) apparatuses in power systems
- More complex system dynamics (e.g. inverter-caused SSR)
- The move to online apparatus condition monitoring

Waveform data
versus
Sync-wave data

SMU – sync-wave measurement unit (a generic name to facilitate description here)

2. Characteristics of synch-wave data & example applications

1. Types of data



2. Forms of data

(for eventual synchronized analysis)

- Raw waveform data
- Derived data (i.e. indices), e.g.
  - *Harmonic phasor*
  - *Magnitude of oscillating power*
  - *Modal impedance*
  - *….*

3. Scheme of data collection and transfer

A. Stored in SMUs and accessed through download (all types)

B. Transmit to a central location when there is a disturbance (type 1 data)

C. Transmit to a central location continuously in multiple snapshots (type 2) or via real-time streaming (type 3)

2. Characteristics of synch-wave data & example applications

Important clarifications:

- <u>Differentiate three concepts about the data:</u>
  - data with precision time information, <= This is about the data
  - synchronized recording of data, <= This is about how data is collected
  - synchronous transfer of (real-time) data. <= This is about how data is transferred

- <u>Modes of data transfer:</u>
  - Real-time => live streaming
  - Delayed => on-demand streaming (including download)

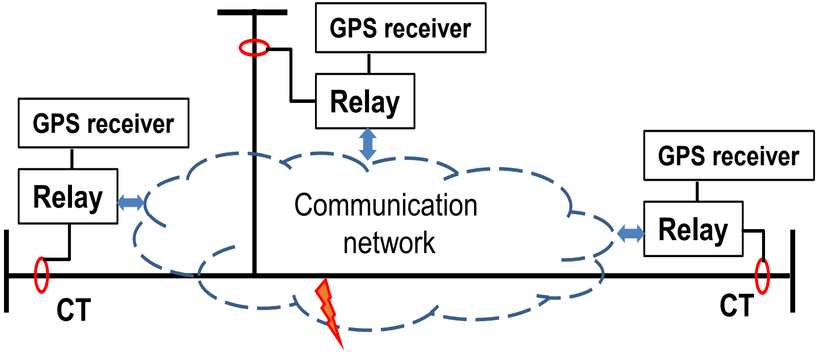
- <u>Central location for synchronized data analysis:</u>
  - It does not mean control center only
  - It can be a substation or even an engineering office

The requirements on the specific features of sync-wave data are <u>highly application dependent</u>

2. Characteristics of synch-wave data & example applications

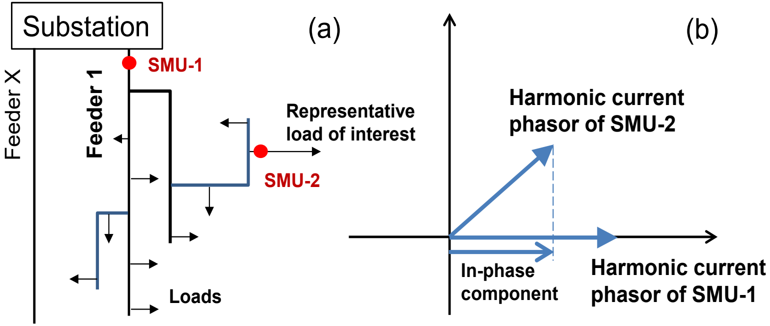
Example 1: Waveform-based line differential protection

- Type 3 (gapless) data => waveform data
- Real-time streaming
- Three central locations: substations
- SMUs are embodied as relays
- Online application with control action



Example 2: Characterization of harmonic cancellation effect

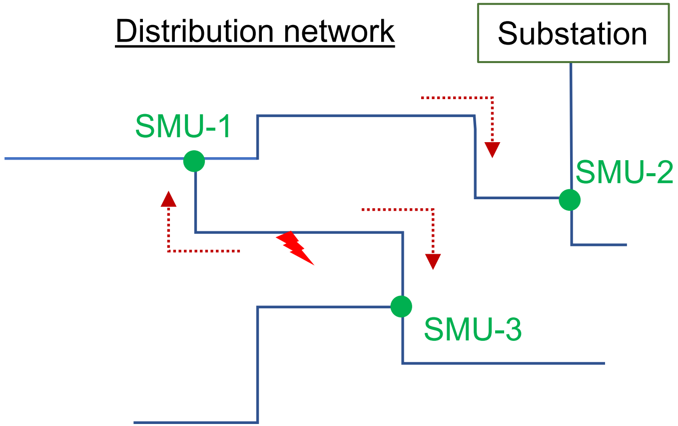
- Type 3 (gapless) data => harmonic phasor
- Access data through download
- Central location: engineering office
- Portable PQ monitors as SMUs
- Offline application



2. Characteristics of synch-wave data & example applications

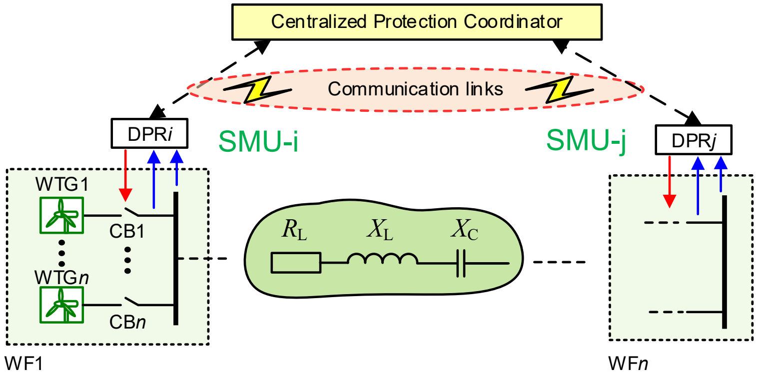
Example 3: Traveling wave-based fault location

- Type 1 (disturbance) data => instant of wave arrival
- Delayed transmission of data using SCADA
- Central location: distribution control center
- SMU = Traveling wave monitoring device
- Online monitoring application (without control action)



Example 4: Mitigation of SSR in wind farms

- Type 1 (disturbance) data => SSR impedance
- Real-time streaming
- Central location: control center
- SMU = Relay-like device (called DPR)
- Online application with control action



2. Characteristics of synch-wave data & example applications

Classification of applications:

1) Offline analysis
2) Online monitoring (no automatic action)
3) Real-time P&C (protection & control)

There are two more examples in the paper

Table I: Characteristics of sync-wave data as affected by applications.

Data Characteristics \ Application types		Offline Analysis	Online Monitoring	Real-time P&C
Data Type	1: Single snapshot		3	4
	2: Multi-snapshot			
	3: Gapless snapshot	2		1
Data Form	Time-domain			1
	Derived form	2	3	4
SMU Type	Stationary		3	1,4
	Portable	2		
Trans-mission Scheme	A: Download	2		
	B: Event-driven		3	4
	C: Streaming			1
Trans. Mode	Real-time			1,4
	Delayed	2	3	
Central location	Control center		3	4
	Substation			1
	Engineering office	2		

We have explained:

- Status and characteristics of sync-wave data
- Various ways to collect and access the data
- Three types of applications

Main takeaway:

How sync-wave data is used is highly dependent on the type of applications. Real-time streaming of the data to control center is only one of the possible approaches

Sharing Our Visions on Sync-wave Data Applications

3. Vision 1 – Platforms of sync-wave applications

There are three application platforms:

Platform No.1: Special purpose sync-wave platforms

- For (real-time) protection & control applications
- Extremely high reliability requirement due to automatic control actions
- Customized, dedicated SMU network is the most acceptable approach
- Consistent with current industry practice
- Examples 1 (line protection) and 4 (SSR mitigation)

It is important to note that a dedicated SMU network does not mean dedicated infrastructures (e.g. BPA's synchrophasor-based Remedial Action Scheme).

3. Vision 1 – Platforms of sync-wave applications

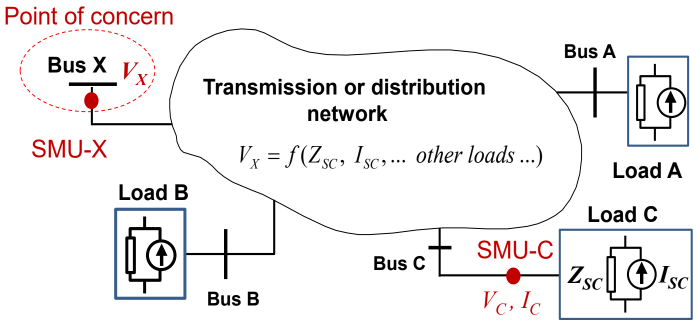
Platform No.2: Multi-Use Sync-wave Platforms

- For online monitoring and offline analysis applications
- Real-time streaming of data is NOT necessary
- Thus a lot more options are available to construct such a network
- Examples 1 (harmonic phasor) and 3 (fault location)

Important features of this SMU network

- On-demand access to data
- Distributed data storage
- Disturbance data streaming

Monitoring the impact of customer C on Bus X

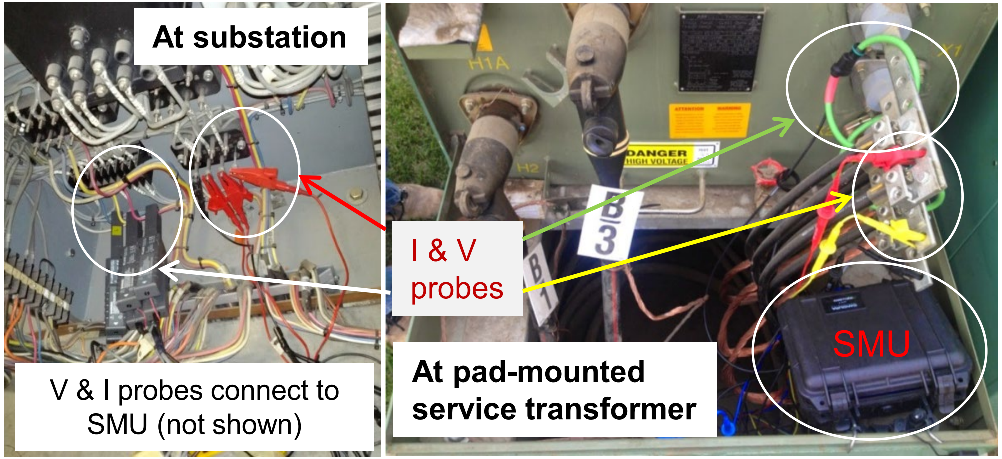


3. Vision 1 – Platforms of sync-wave applications

Platform No.3: Mobile Sync-wave Platforms Using Portable SMUs

- For offline analysis, e.g. troubleshooting, model validation, forensic analysis etc.
- Can be deployed at almost any locations with little infrastructure support
- A very important tool to support university research including emulating PMUs

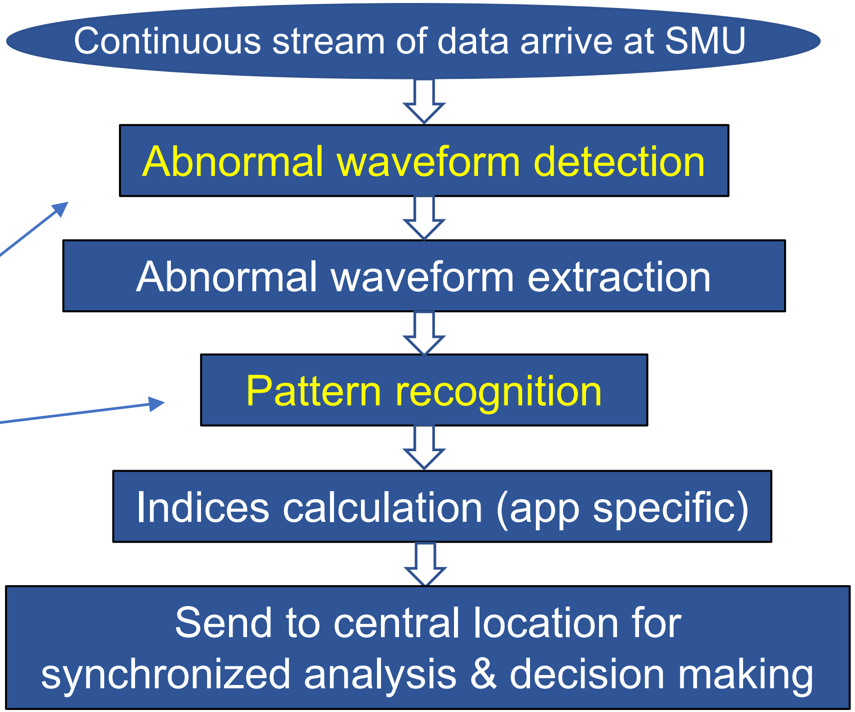
Installation of two SMUs
(Portable PQ monitors)
of example 2



3. Vision 1 – Platforms of sync-wave applications

Need to research and develop general-purpose data analytics algorithms

- Most useful sync-waves are those that contain changes or disturbances (called abnormal waveforms here)
- Focusing on abnormal data reduce capacity requirements on infrastructures
- Need to develop general-purpose abnormality detection & pattern recognition algorithms
- It is also useful to research application specific data analytics algorithms (such as extracting SSR indices)



SMU is the best location to perform the above analysis

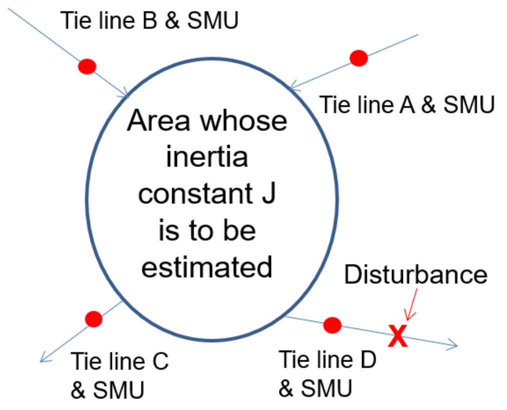
4. Vision 2 – Strategies to develop sync-wave based applications

Unique strengths of sync-wave data

- Waveform is the most authentic data about the behaviors of system and its apparatuses
- It is also the most granular data obtainable
- Data from <u>multiple locations</u> can now be <u>analyzed together</u> due to sync-wave feature

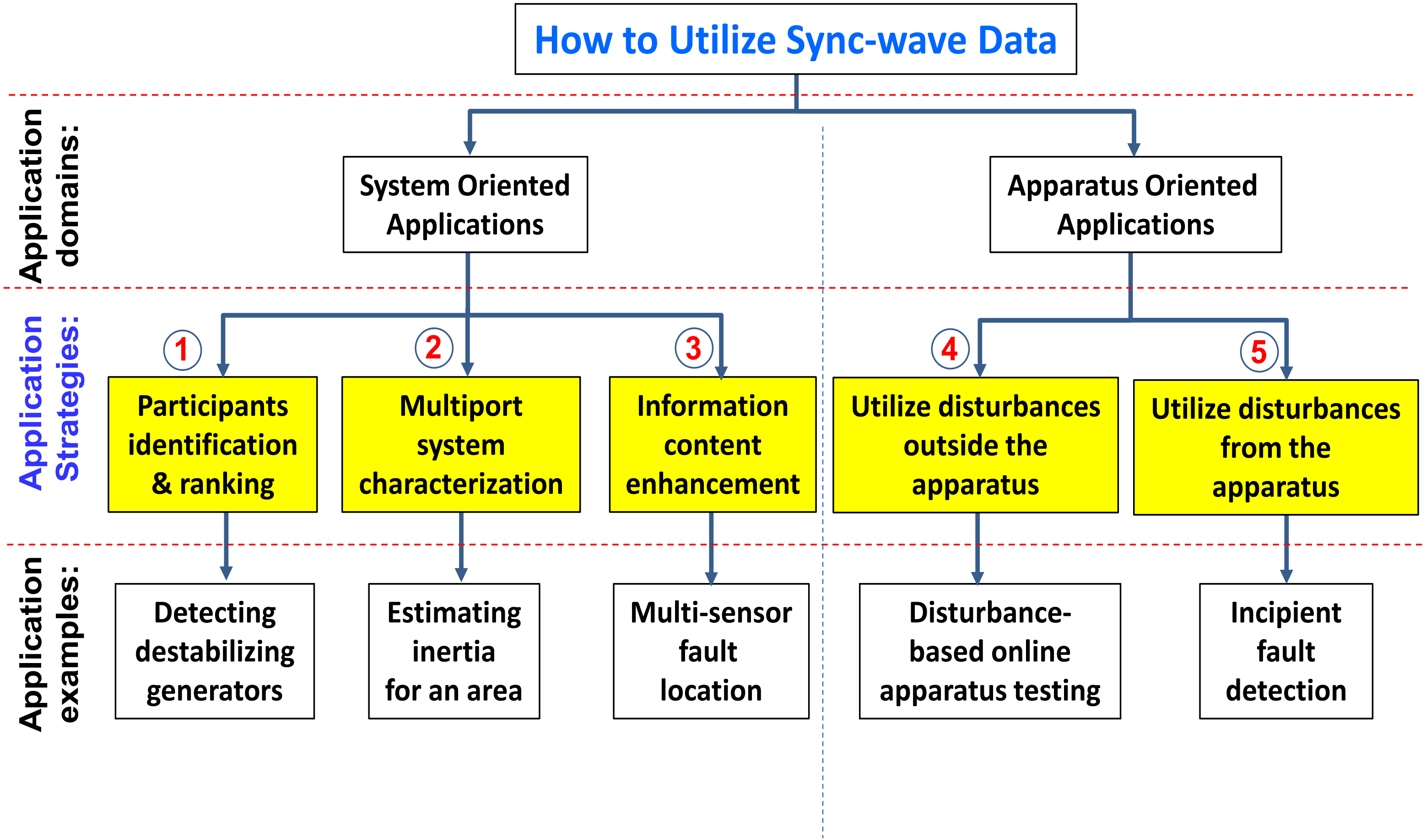
Values of multi-location data:

- <u>Help to solve location related problems</u>, e.g. which inverter triggers instability?
- <u>Support multi-port network/component characterization</u>: e.g. inertia of a regional power system
- <u>Enhance information using multiple data</u>: e.g. differential protection and fault location



An example multiport problem

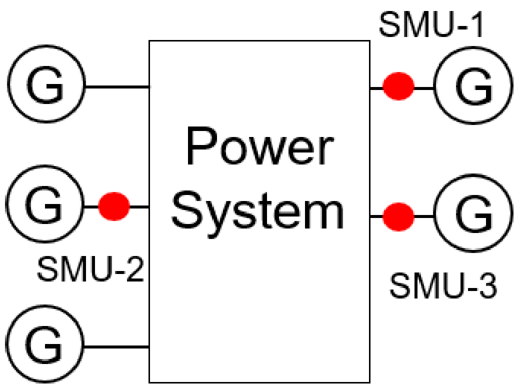
4. Vision 2 – Strategies to develop sync-wave based applications



4. Vision 2 – Strategies to develop sync-wave based applications

Example application 1

Which generators are causing system oscillation?

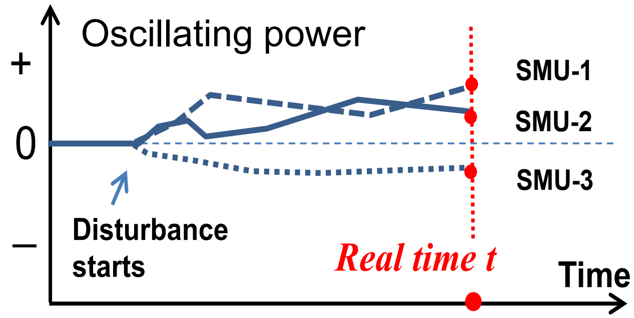


Traditional method:

Offline eigen-analysis and participation factors

Sync-wave based method (one potential idea):

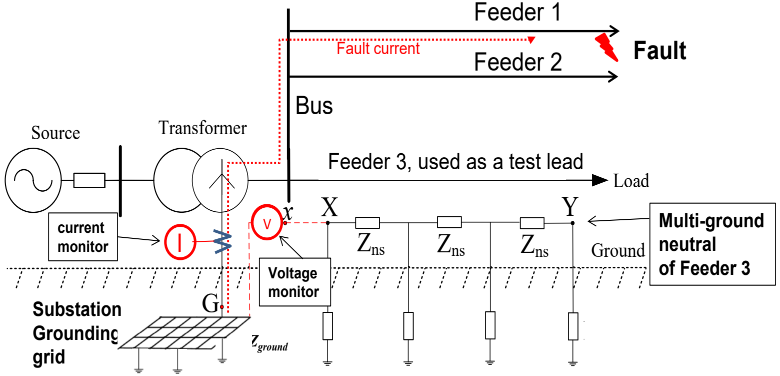
- Oscillation is driven by (back & forth) energy transfer
- i.e. there is a power oscillating at certain frequencies
- We could determine this power at each generator
- Comparing the power behaviors of the generators could pinpoint the critical generators
- Comparison can only be done using sync-waves since the powers need to be compared



Example application 2: Equipment monitoring

- Equipment health check is often done using occasional off-line tests
- We can use natural disturbances as “test signals” to perform online “testing”
- Disturbance data often need to be collected from multiple locations
- Sync-waves make the idea of disturbance-based online monitoring possible
- Thus transforming offline equipment monitoring into online monitoring

Problem to solve: find the impedance of substation grounding grid



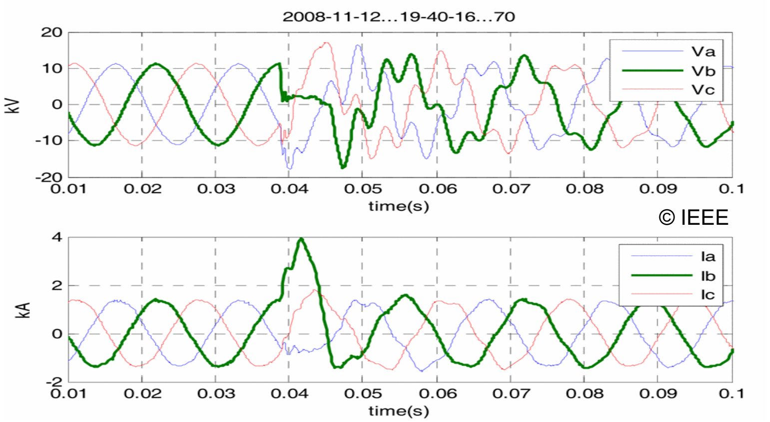
$$Z_{Ground}(f) = \frac{F\{v_{during\_fault}(t) - v_{pre\_fault}(t')\}}{F\{i_{during\_fault}(t) - i_{pre\_fault}(t')\}}$$

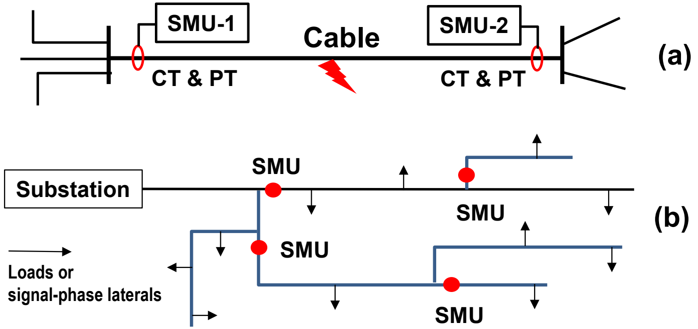
4. Vision 2 – Strategies to develop sync-wave based applications

Example application 3: Incipient fault detection

- Incipient faults are early signs of pending equipment failures
- It shows up as anormal waveforms, and cannot be detected by relays
- Multi-location sync-wave data can greatly help the detection and location of incipient faults
- The idea could help to prevent power-line related forest fires

This is a monitoring application





The paper also presents a 3rd vision – how to work together through technical committees and data/algorithm sharing

4. Main takeaways regarding the two visions:

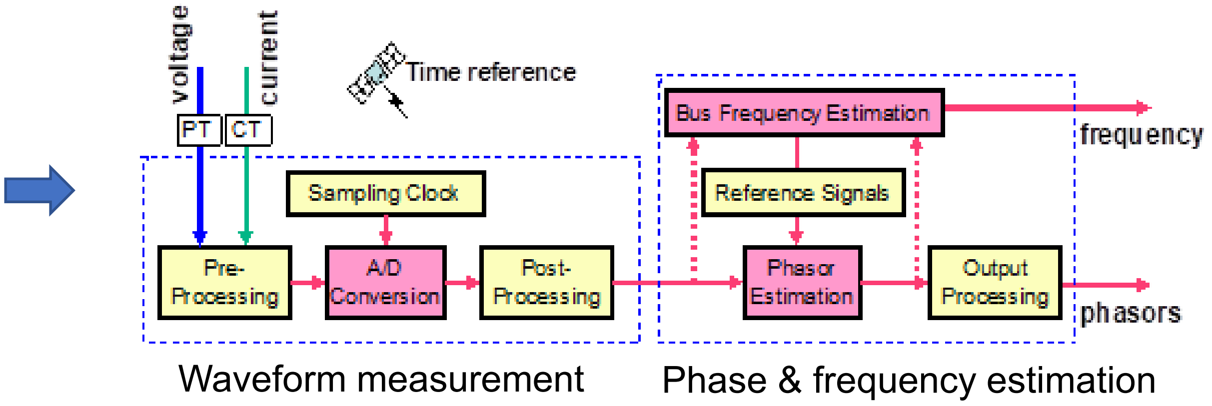
- Real-time streaming of sync-wave data is not necessary for many applications. It is needed mainly for a dedicated SMU platform serving a specific control function
- Two other platforms, multi-use (on-demand access) platform and mobile platform are likely to be more useful, at least at the early stage of sync-wave adoption
- Sync-wave data can support both system and apparatus oriented applications
- The main strength of sync-wave is to enable integrated analysis of multi-location data, thus sync-wave is especially useful for solving problems involving:
    - Interactions of multiple components (e.g. ranking, contributor identification)
    - Multiport systems or subsystems (e.g. characterizing an area instead of a component)
    - Cross-referenced information extraction (e.g. differential analysis)

Some thoughts on
Sync-wave versus Synchrophasor

5. Sync-wave versus Synchrophasor

- Synchrophasors are calculated from waveforms, i.e. a derived form of sync-wave
- Information is lost when transforming waveform data into a single index
- Anomaly in a waveform cannot be captured by phasors
- Since many applications don't require real-time streaming of waveform data, the main advantage of phasor – less demand on communication – does not really exist

Process of synchrophasor measurement

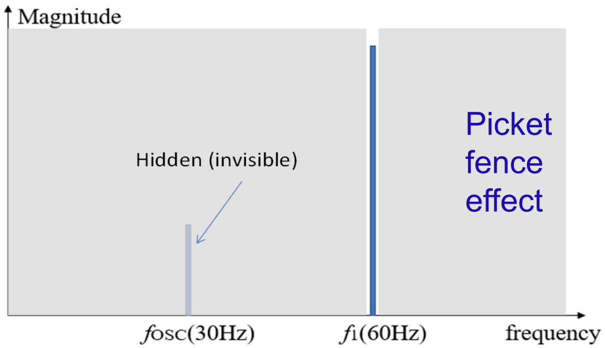


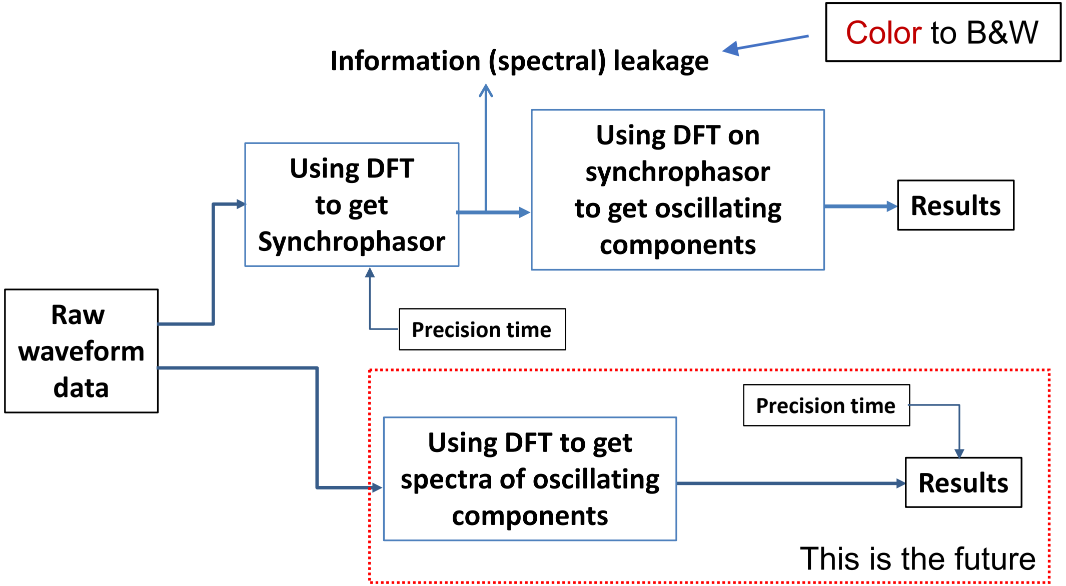
5. Sync-wave versus Synchrophasor

Example - Power oscillation monitoring

$$v = V_1 \cos(2\pi f_1 t) + V_{OSC} e^{-\alpha t} \cos(2\pi f_{OSC} t + \theta_{OSC})$$

$$i = I_1 \cos(2\pi f_1 t) + I_{OSC} e^{-\alpha t} \cos(2\pi f_{OSC} t + \delta_{OSC})$$





	Actual/SMU	Calculated from phasor
V_1	75∠0°	76.47∠0°
I_1	40∠0°	41.8∠0°
f_{OSC}	30Hz	30Hz
V_{OSC}	25∠0°	10.62∠88°
I_{OSC}	20∠0°	8.5∠88°
P_{OSC}	250	45

Why tie up our hands with a processed data?

Why limit our imagination to one complex number?

We deserve more!

6. Conclusions & Main takeaways

The trend and opportunity:

- Waveforms are the most authentic and granular data revealing power system behaviors
- Phasor data provides limited information in comparison with waveform data
- Modern power systems need to be monitored and analyzed using waveform data
- Sync-wave makes it possible to utilize waveform data from multiple locations
- Hardware technologies of sync-wave measurement are already available
- Thus, a great opportunity for power engineering innovations has arrived

6. Conclusions & Main takeaways

This webinar and paper have shared

- Visions on three platforms of sync-wave applications: dedicated, multi-use and mobile platforms
- The need for data analytics research on abnormal waveform detection and abnormality pattern recognition
- Five strategies to develop applications for both system and apparatus oriented applications. The most promising ones include:

  1) Participants identification, ranking and targeted actions for system-wide problems
  2) Migrating offline apparatus monitoring into online through utilizing SMU measured natural disturbances

Thank you for attending

We welcome
any questions and comments
you may have

One suggestion to NASPI

There is a need to establish consensus terminologies such as “sync-wave” and “SMU”

NASPI can provide an immediate leadership to finalize the terminologies