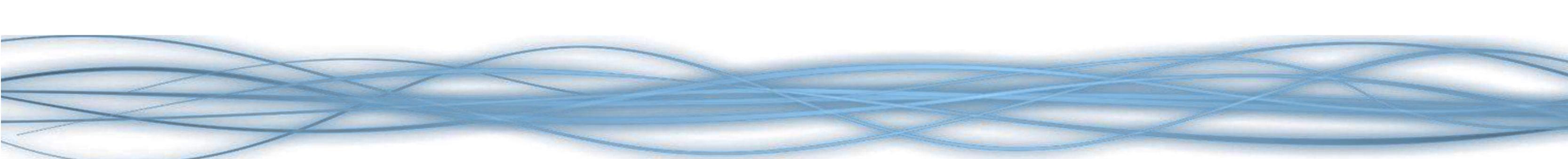


OPAL-RT TECHNOLOGIES

FROM IMAGINATION TO REAL-TIME

Testing PMUs with HYPERSIM



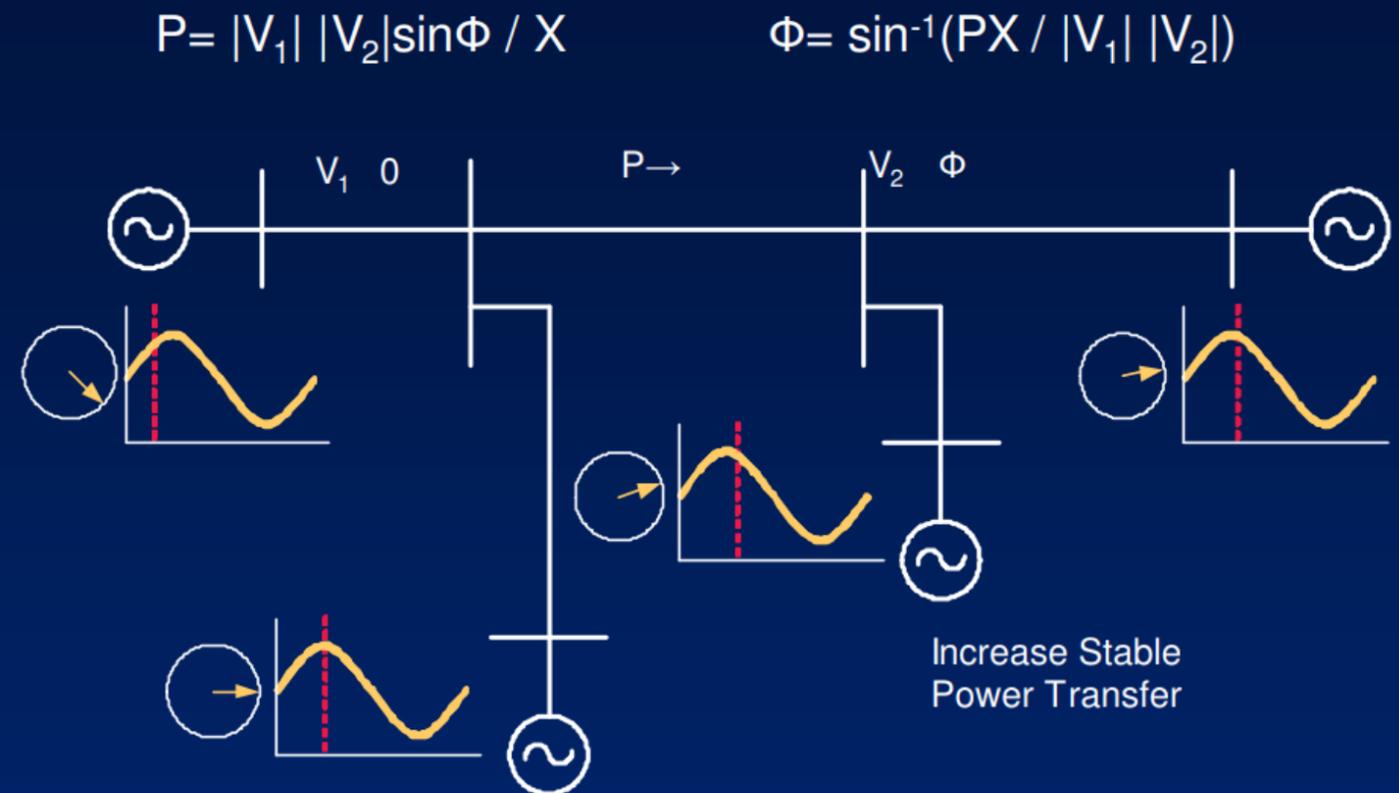


Phasor Measurement Unit

PMU(Phasor Measurement Unit)

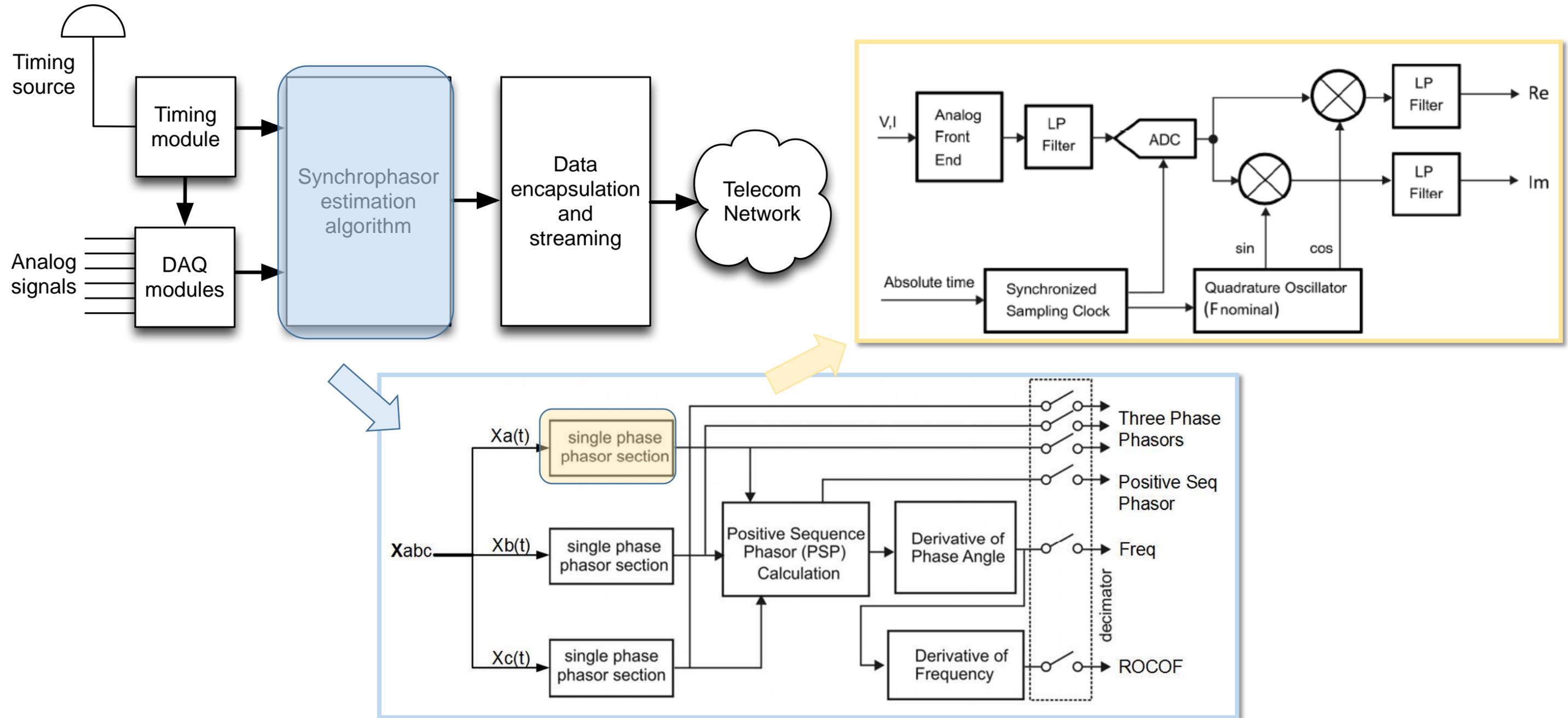
- synchrophasorは、位相によって記述される量の時間同期測定を意味する。
- PMUは、周波数や位相角などの計算されたパラメーターで電圧と電流を測定する。
- 異なる場所のPMUによって行われた測定は、時間同期される。

Synchrophasors Provide a “Snapshot” of the Power System



$$x(t) = X_m \cos(\omega_0 t + \phi) = X_m \cos(2\pi f_0 t + \phi)$$

PMUの使用概念



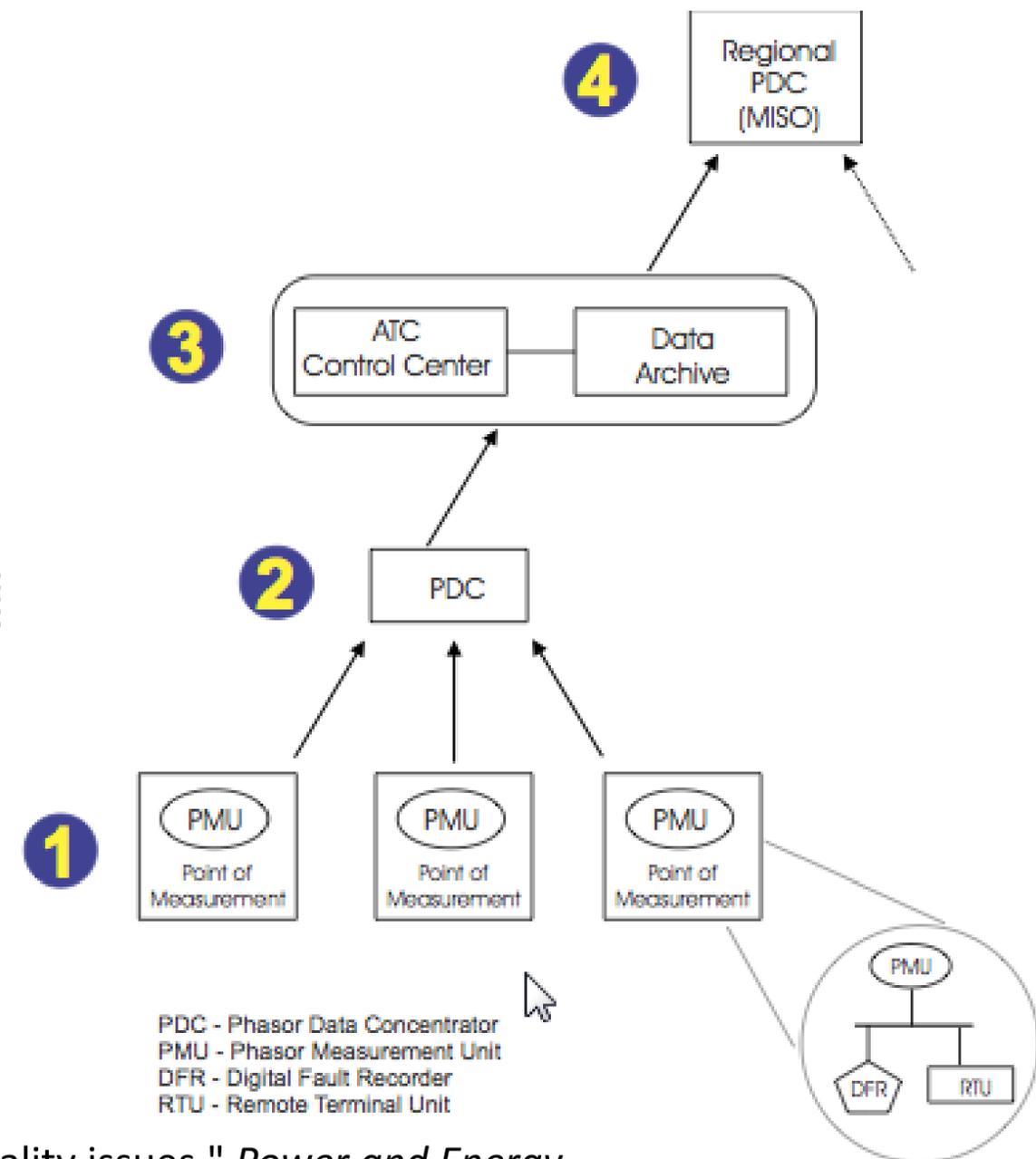
PMUデータフロー

- PMU
- Phasor Data Concentrator (PDC)
複数のPMUからデータを受信して時間同期し、リアルタイムに出カデータストリームを生成すること
- データ保存
- Regional PDC
PDCの時刻同期やアカウント情報の変更などを管理

NASPI: North America Synchro Phasor Initiative

- <https://www.naspi.org/>
- <http://openpdc.codeplex.com/>

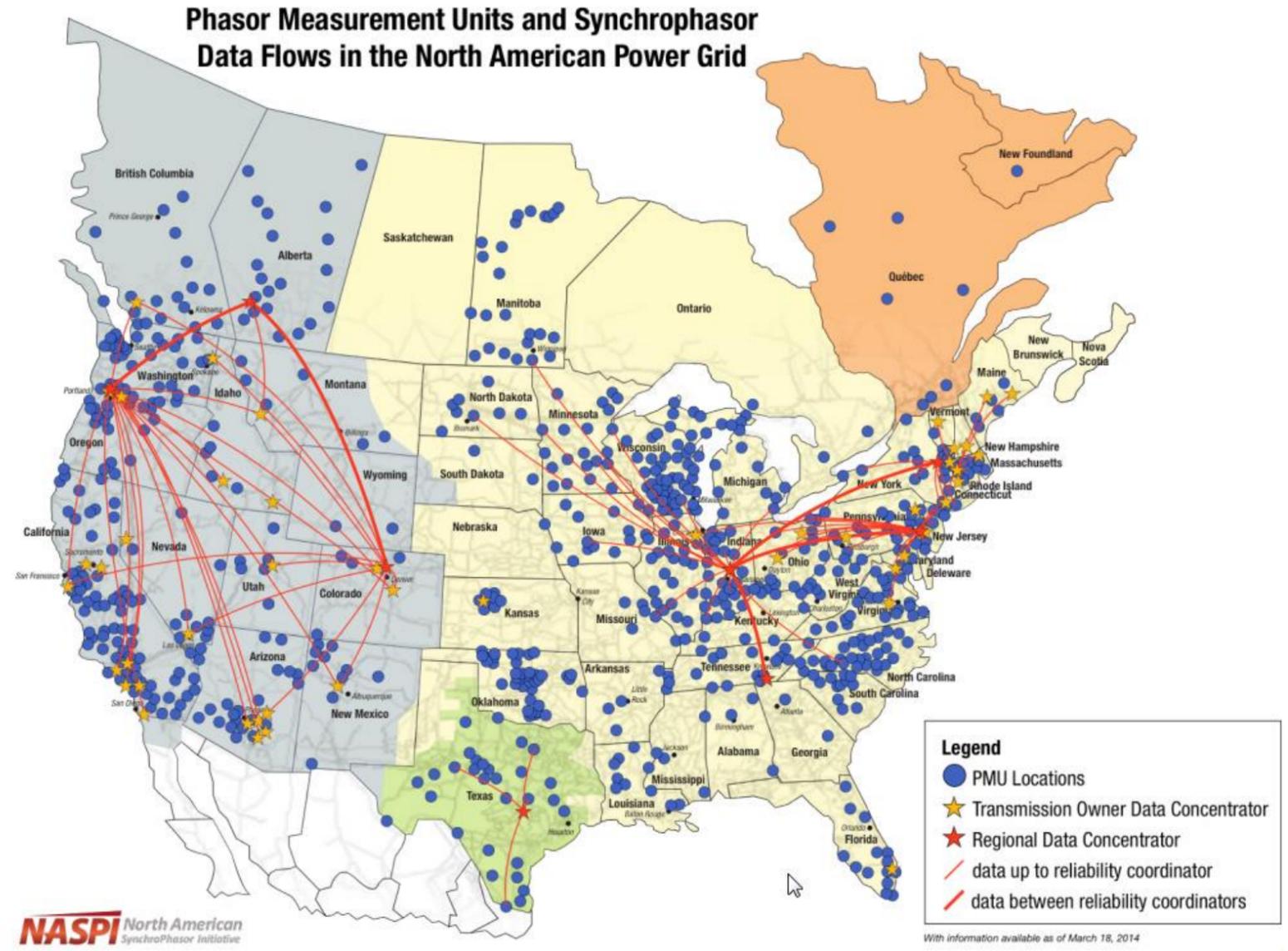
The Open Source Phasor Data Concentrator



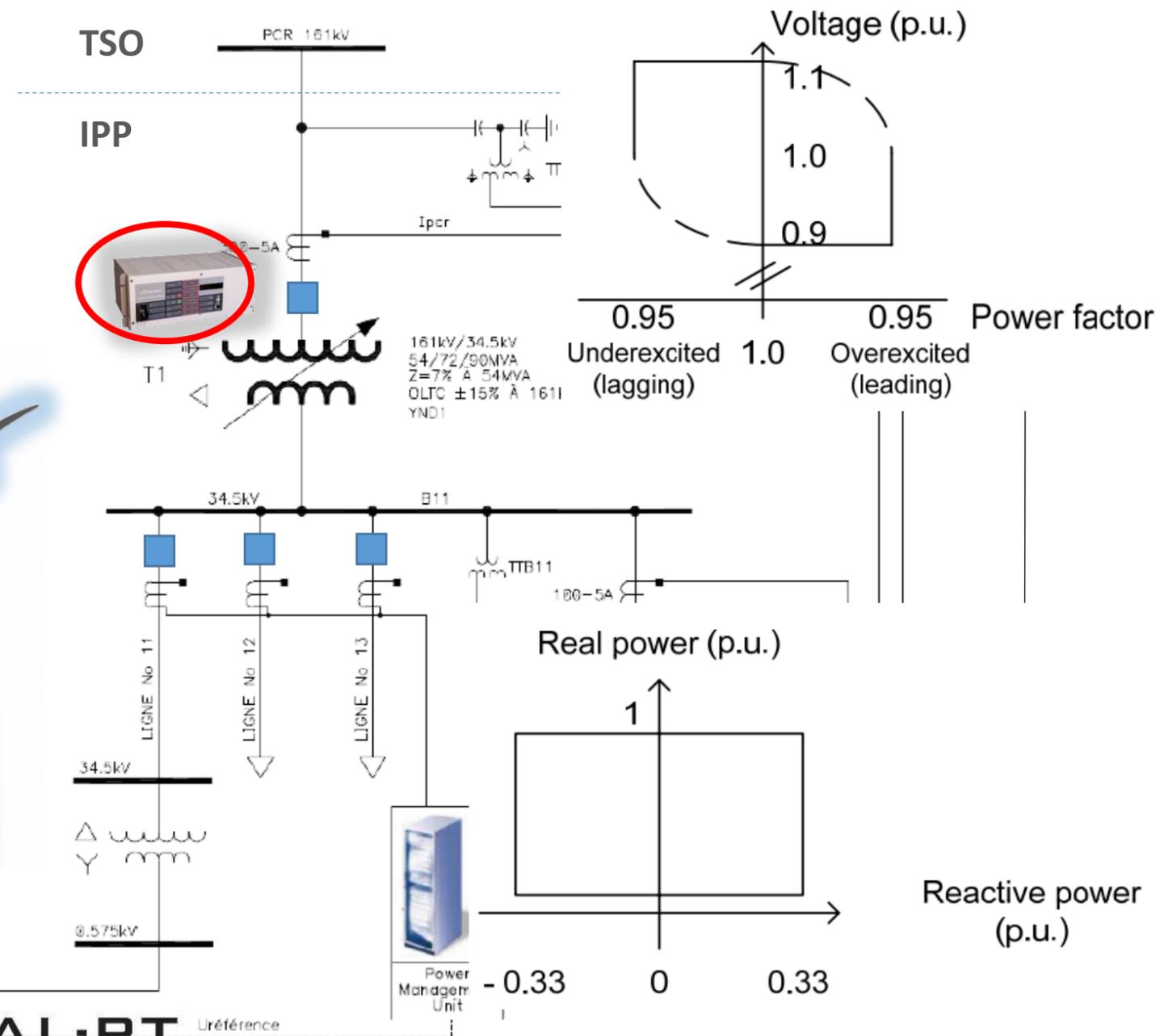
Kirihara, Kenta, et al. "Investigating synchrophasor data quality issues." *Power and Energy Conference at Illinois (PECI), 2014*. IEEE, 2014.

PMU 導入の目的

- 米国およびカナダに展開された1700台のPMU
- 主なアプリ
 - 状況認識と広域監視
 - リアルタイム操作と状態推定
 - 電力システムの計画とモデル検証
 - 外乱と停電の事後分析



モデルベース設計- Mont-Rothery Wind Farm in Canada

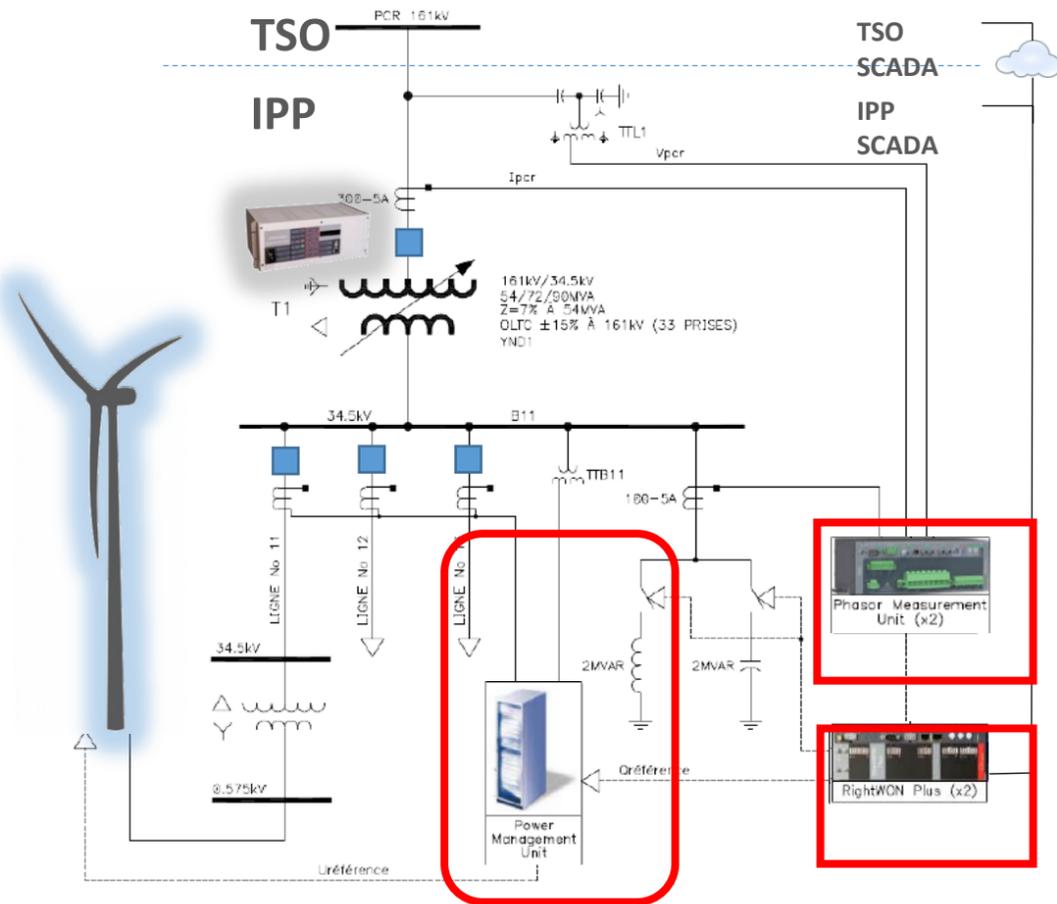


- 風力発電所およびその他の独立系電力生産者 (IPP) は、ネットワークグリッド要件を遵守する必要がある

- その為、複雑で高価な静的VAR補償器 (SVC) および機械的に切り替えられるコンデンサバンクとシャントリアクトルを設置することを意味する

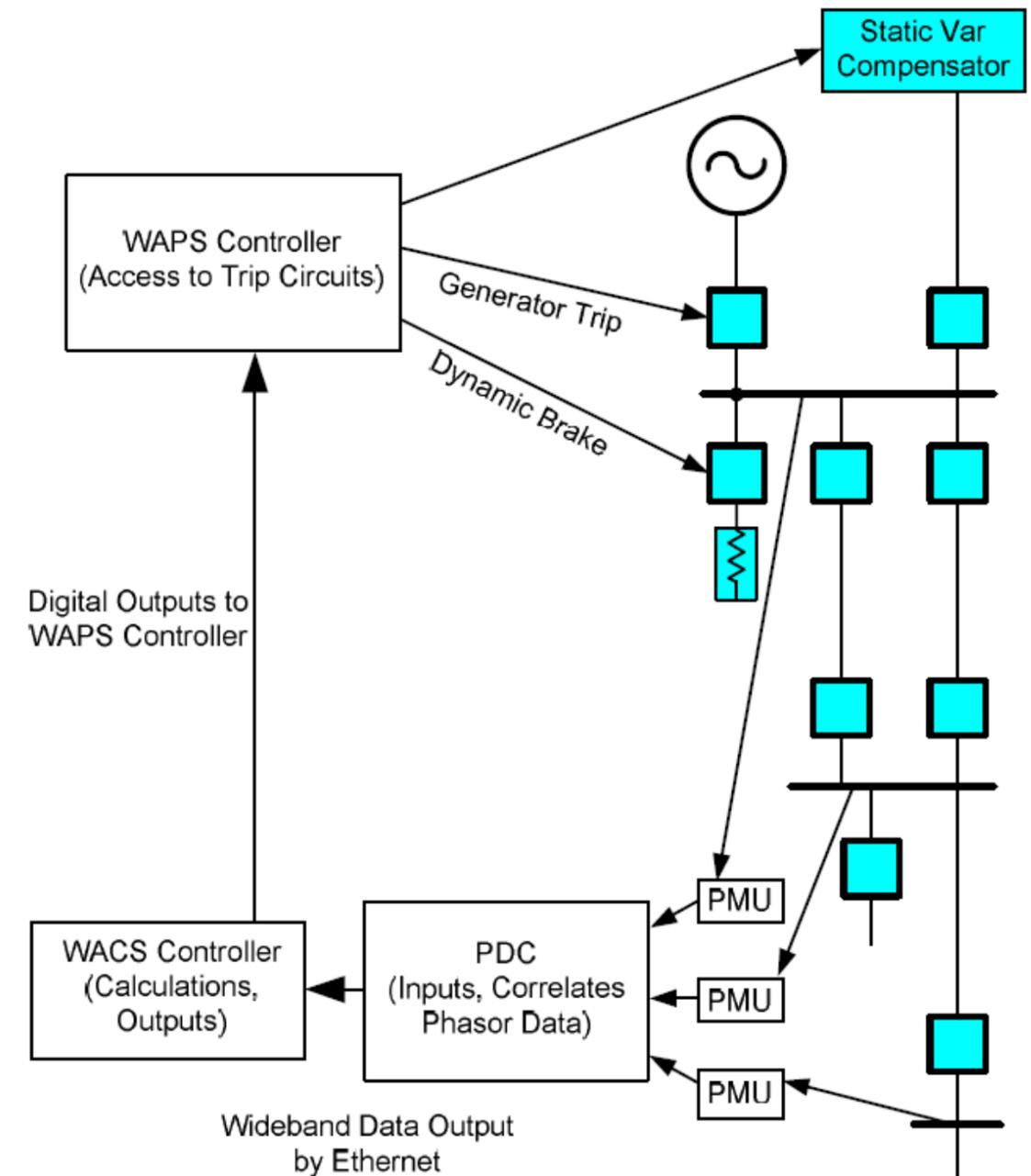
モデルベース設計- Mont-Rothery Wind Farm in Canada

- PMUを使用して、PCCで電圧と電流を測定 (120 fps)
- 産業用コントローラーはC37.118ストリームを受信し、PIDループを使用して計算、修正を行い、決定を下す
- コントローラーは風力発電制御装置に設定値を送信。
- コントローラーは、コンデンサーバンクとシャントリアクトルも制御し、要件を満たす



Bonneville 電源管理局SIPS

- SIPS (System integrity protection schemes)
- システム整合性保護スキーム (SIPS)
 - 脱調状態の検出
 - エリア間電力変動の特定。
 - 多端子変電所母線の保護。
 - 電流および電圧の測定エラーを特定。



脱調検出

$$\delta_k = V_{1_Angk}^{Relay1} - V_{1_Angk}^{Relay2} \quad (1)$$

$$S_{fk} = \frac{(\delta_k - \delta_{k-1})}{360} \text{MRATE} \quad (2)$$

$$A_{fk} = (S_{fk} - S_{fk-1}) \cdot \text{MRATE} \quad (3)$$

where:

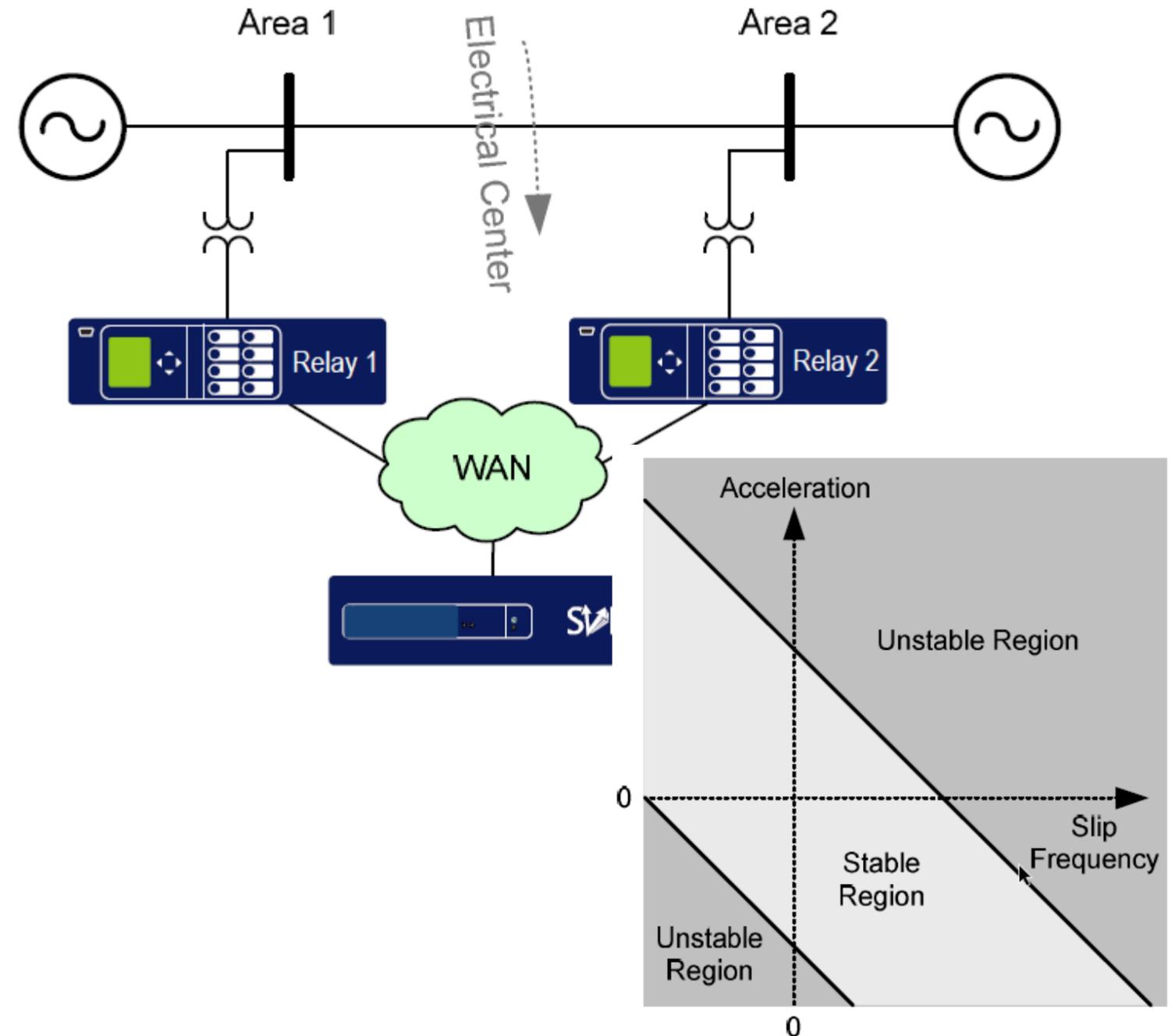
$V_{1_Angk}^{Relay1}$ is the positive-sequence voltage angle of Relay 1 at the k processing interval

$V_{1_Angk}^{Relay2}$ is the positive-sequence voltage angle of Relay 2 at the k processing interval

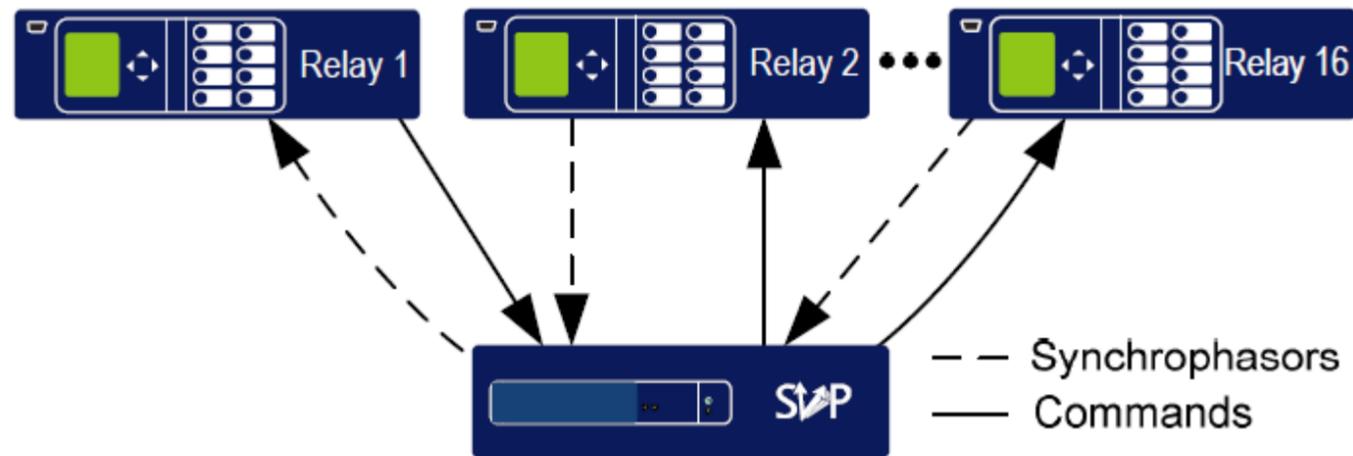
S_{fk} is the slip frequency at the k processing interval

A_{fk} is the acceleration at the k processing interval

MRATE is the synchrophasor message rate

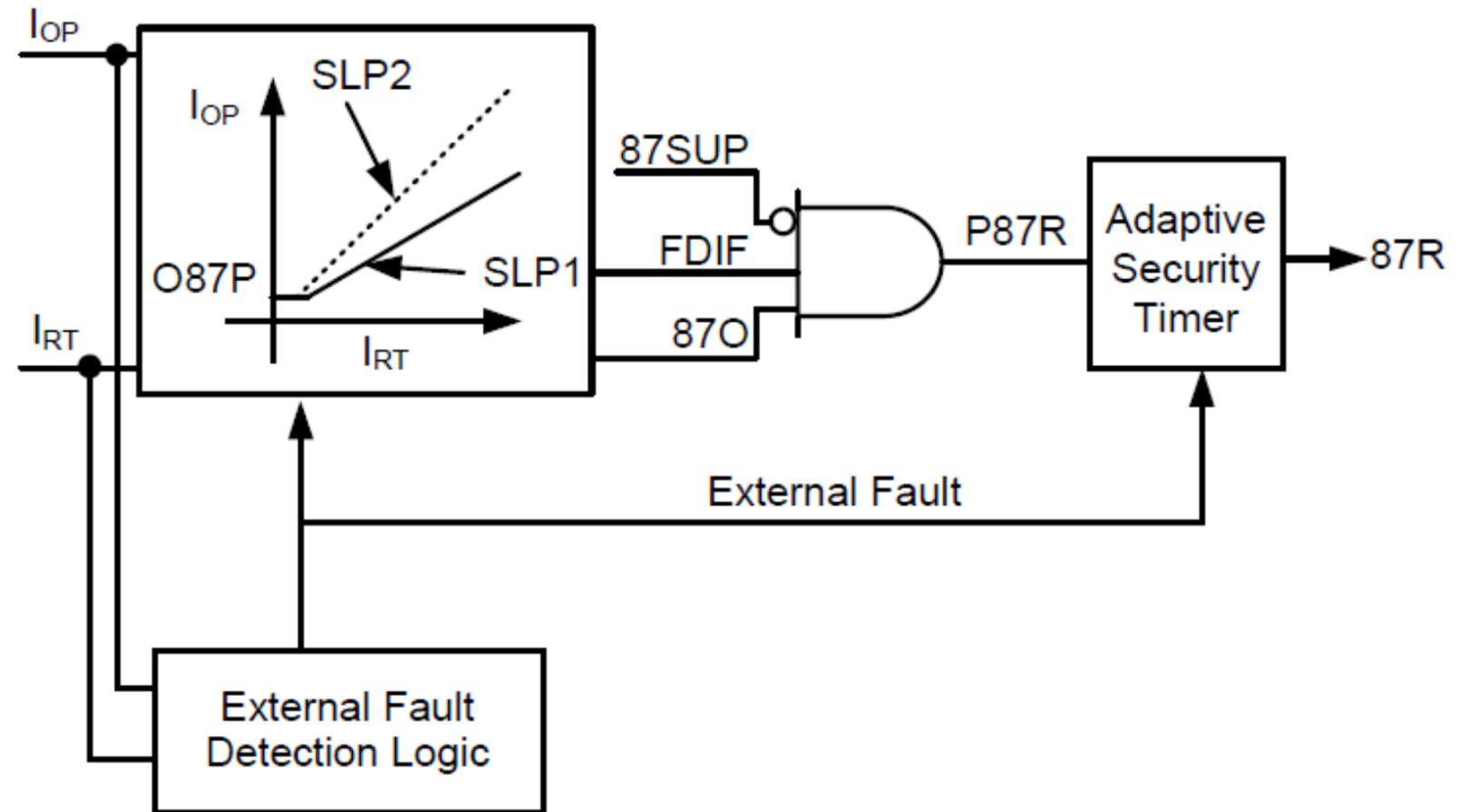


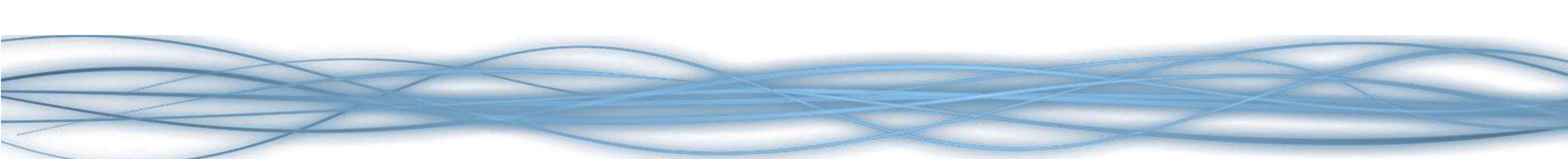
分散母線差動保護



$$I_{RT} = |I_{01}| + |I_{02}| + \dots + |I_{64}|$$

$$I_{OP} = |I_{01}| + |I_{02}| + \dots + |I_{64}|$$





PMUの認識

重要なパラメータ

- 通信
 - TCP or UDP
 - Port number
 - Peer IP address
- 時間同期
 - 1PPS
 - IRIG-B
 - IEEE 1588
- 位相データ
 - Voltage
 - Current
 - Sequence
- システムパラメータ
 - Nominal frequency
 - Performance class
 - Reporting rate

Vizimax PMU 構成

- 通信方法
- ピアIPアドレス
- ポートNo
- パフォーマンスクラス
- レポートレート

The screenshot shows the 'Vizimax Commissioning Tool' window. The left sidebar displays a tree view under 'PMU Application' with 'Reportings' expanded to 'C37.118' and 'Reporting #1' selected. The main area shows 'Reporting #1: Reporting #1 Communication Parameters' with a search bar and a 'Clear' button. The configuration is organized into sections: 'Link' (Communication Method: TCP - Only Method, Peer IP Address: 255.255.255.255, Peer UDP Port: 4713), 'Misc' (Configuration Change Count: 0, Debug Level: NONE, Enabled: checked, Performance Class: Class M, Rate: 60 Frame Per Second, Station Name (STN): Reporting1, Stream ID number (IDCODE): 1, Version: Version 2 (IEEE Std C37.118-2.2011)), and 'Spontaneous Data Transmission' (Spontaneous Configuration and Header frame rate (s): 10). A note at the bottom states 'Reporting Data Rate for this reporting instance.' The bottom right has 'Save' and 'Close' buttons. The version 'v2.0.2.176' is visible in the bottom left corner.

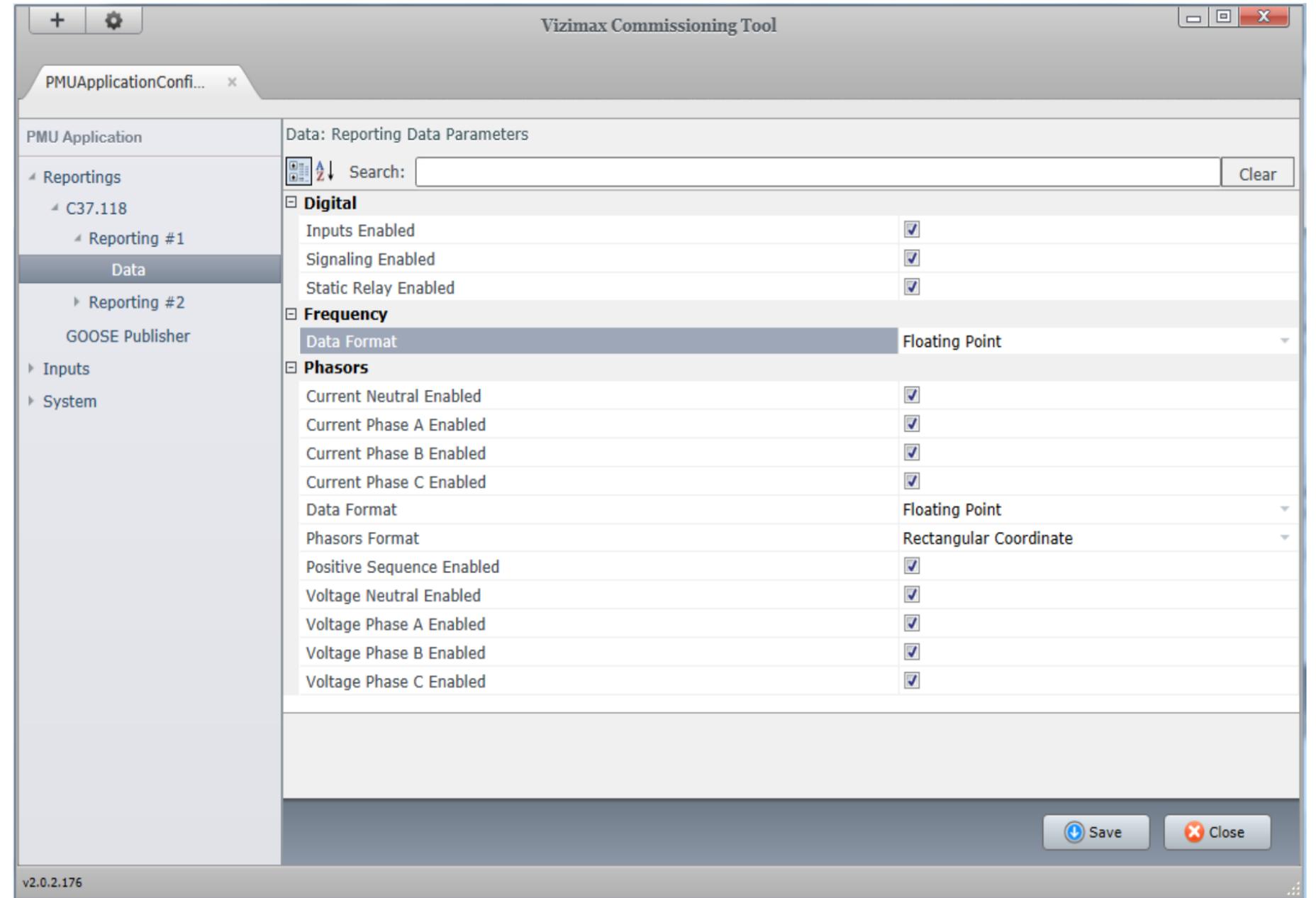
Section	Parameter	Value
Link	Communication Method	TCP - Only Method
	Peer IP Address	255.255.255.255
	Peer UDP Port	4713
Misc	Configuration Change Count	0
	Debug Level	NONE
	Enabled	<input checked="" type="checkbox"/>
	Performance Class	Class M
	Rate	60 Frame Per Second
	Station Name (STN)	Reporting1
	Stream ID number (IDCODE)	1
Version	Version 2 (IEEE Std C37.118-2.2011)	
Spontaneous Data Transmission	Spontaneous Configuration and Header frame rate (s)	10

Vizimax PMU 構成

- PMUストリームに含めるデータを選択

位相

- 矩形
- 極性



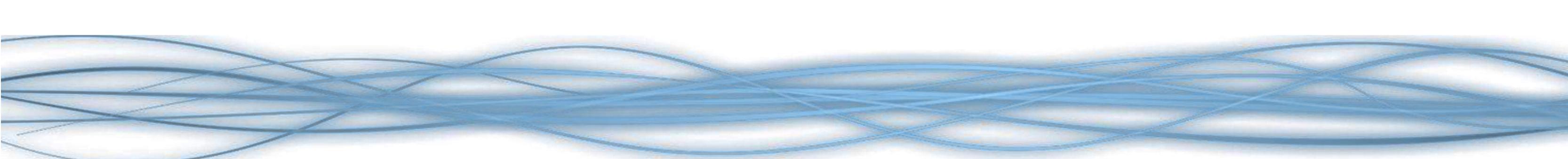
Vizimax PMU 構成

- 時刻同期
 - PTP – 1588
 - IRIG-B
 - PPS

The screenshot displays the 'Vizimax Commissioning Tool' interface. The main window is titled 'PMUSystemConfig.vx...' and shows the configuration for 'PTP-1588: PTP-1588 clock configuration.'. The left sidebar is expanded to 'System Time' > 'Clocks' > 'PTP-1588'. The main area shows a table of configuration parameters under the 'Misc' section.

Parameter	Value
Debug Level	NONE
Enabled	<input type="checkbox"/>
Priority 1	255
Priority 2	255
PTP Clock Class	Slave-only (255)
PTP Domain Number	0
PTP profile	Default P2P profile
Servo locking target inaccuracy (ns)	200
Sync Message Mode	1 Step
Worst Network Path Inaccuracy (ns)	0

At the bottom of the window, there are 'Save' and 'Close' buttons. The version number 'v2.0.2.176' is visible in the bottom left corner.



RTSとPMUの接続

C37.118 Master configuration

- .OPAL and .IO

```
OPAL-1.0 Object
C37118::Master::Configuration {
  autoRunAcq=1
  listeningTimeoutMs=30000
  specialAction=
  copyOnWrite=0
  locked=0
  name=
  versioned=0
  pmuConnectionList {
    item {
      alias=PDC1
      id=1
      ip=192.168.3.185
      localConfigPath=/export/local/ssr/hyconfig/
      localUdpPort=0
      port=7200
      protocol=TCP
    }
  }
  history=
  parent=
}
```

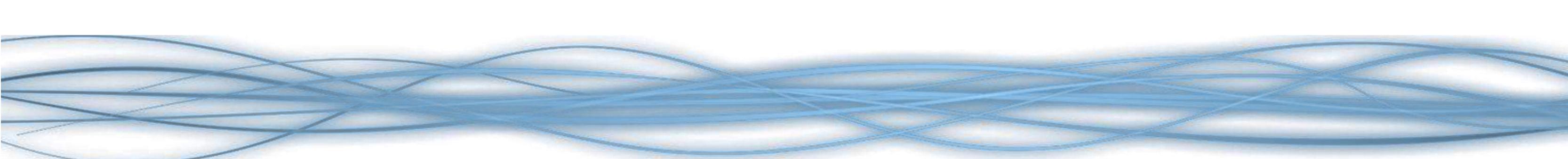
AD	18037	18037	PDC1	PDC1/Error	none
AD	18038	18038	PDC1	PDC1/FracSec	none
AD	18039	18039	PDC1	PDC1/Freq	none
AD	18040	18040	PDC1	PDC1/I-PHASOR.angle	none
AD	18041	18041	PDC1	PDC1/I-PHASOR.factor	none
AD	18042	18042	PDC1	PDC1/I-PHASOR.magnitude	none
AD	18043	18043	PDC1	PDC1/ROCOF	none
AD	18044	18044	PDC1	PDC1/SOC	none
AD	18045	18045	PDC1	PDC1/Stat.configChange	none
AD	18046	18046	PDC1	PDC1/Stat.dataError	none
AD	18047	18047	PDC1	PDC1/Stat.dataModified	none
AD	18048	18048	PDC1	PDC1/Stat.dataSorting	none
AD	18049	18049	PDC1	PDC1/Stat.inSync	none
AD	18050	18050	PDC1	PDC1/Stat.timeQuality	none
AD	18051	18051	PDC1	PDC1/Stat.triggerReason	none
AD	18052	18052	PDC1	PDC1/Stat.unlockedTime	none
AD	18053	18053	PDC1	PDC1/Status	none
AD	18054	18054	PDC1	PDC1/Timebase	none
AD	18055	18055	PDC1	PDC1/V-PHASOR.angle	none
AD	18056	18056	PDC1	PDC1/V-PHASOR.factor	none
AD	18057	18057	PDC1	PDC1/V-PHASOR.magnitude	none

PMU Connection Tester

- Tcp
- Host IP
- Port number
- Device ID
- Settings - ForceIPv4 - True

The screenshot displays the PMU Connection Tester application window. The interface is divided into several sections:

- Connection Parameters:** Includes tabs for Tcp, Udp, Serial, and File. The Tcp tab is active, showing Host IP (192.168.3.71), Port (7200), and a checkbox for "Establish Tcp Server". The Protocol is set to IEEE C37.118.2-2011, and the Device ID Code is 1. A "Send" button is available for the command "Disable Real-time Data".
- Configuration Frame:** Shows PMU ID Code (1), OpalRT-PMU1, Phasor (V: V-PHASOR), 2 Phasors, 2 Analogs, 2 Digitals, and a Nominal Frequency of 60 Hz. Power and Vars are both 0.0000.
- Graph:** Displays two waveforms: V-PHASOR (black line) and I-PHASOR (red line). The V-PHASOR graph shows a frequency of 60.1672 Hz. The I-PHASOR graph shows a frequency of 60.0756 Hz. The configured frame rate is 20 frames/second.
- Real-time Frame Detail:** Shows a DataFrame with the following details: Time: 1970-01-01 00:00:26.050, Frequency: 60.0610 Hz, Angle: 177.748696783435°, Magnitude: 0.0000 (0.0000) kV, and Display set to Hexadecimal. The frame data is shown in hexadecimal: AA 01 00 2A 00 01 00 00 00 1A 0F 00 C3 50 00 00 00 04 79 2F 00 03 63 5F 00 3D 00 00 3E E8 03 59 3F 68 03 59 00 00 00 00 BF 5B.
- Status Bar:** Shows Total frames: 0, Frames/sec: 0.0000, Total bytes: 0, Bit rate (mbps): 0.0000, and Queued buffers: 0.



HYPERSIMのPMU追従テスト

IEEE Std. C37.118.1の概要

- 規格の目的
 - PMUの測定精度、記録時間、評価基準を定義
 - IEEE Std. C37.242
 - IEEE Std C37.118.1a™-2014
 - IEEE 同期測定テスト仕様

IEEE STANDARDS ASSOCIATION



**IEEE Standard for Synchrophasor
Measurements for Power Systems**

IEEE STANDARDS ASSOCIATION



IEEE Guide for Synchronization,
Calibration, Testing, and Installation of
Phasor Measurement Units (PMUs) for
Power System Protection and Control

IEEE STANDARDS ASSOCIATION



IEEE Standard for Synchrophasor
Measurements for Power Systems

Amendment 1: Modification of Selected
Performance Requirements

**IEEE Synchrophasor
Measurement Test Suite
Specification**

A Glance at the IEEE Std. C37.118.1

- P-class: 保護機能
 - レスポンスは速いが精度はやや落ちる
- M-class: 測定機能
 - レスポンスは遅いが 精度は良い

• 記録レート

System frequency	50 Hz			60 Hz					
Reporting rates (F_s —frames per second)	10	25	50	10	12	15	20	30	60

IEEE STANDARDS ASSOCIATION

IEEE

IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE STANDARDS ASSOCIATION

IEEE

IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control

IEEE STANDARDS ASSOCIATION

IEEE

IEEE Standard for Synchrophasor Measurements for Power Systems

Amendment 1: Modification of Selected Performance Requirements

IEEE Synchrophasor Measurement Test Suite Specification

測定精度の評価-基準

- 定常状態テスト基準

- 周波数エラー

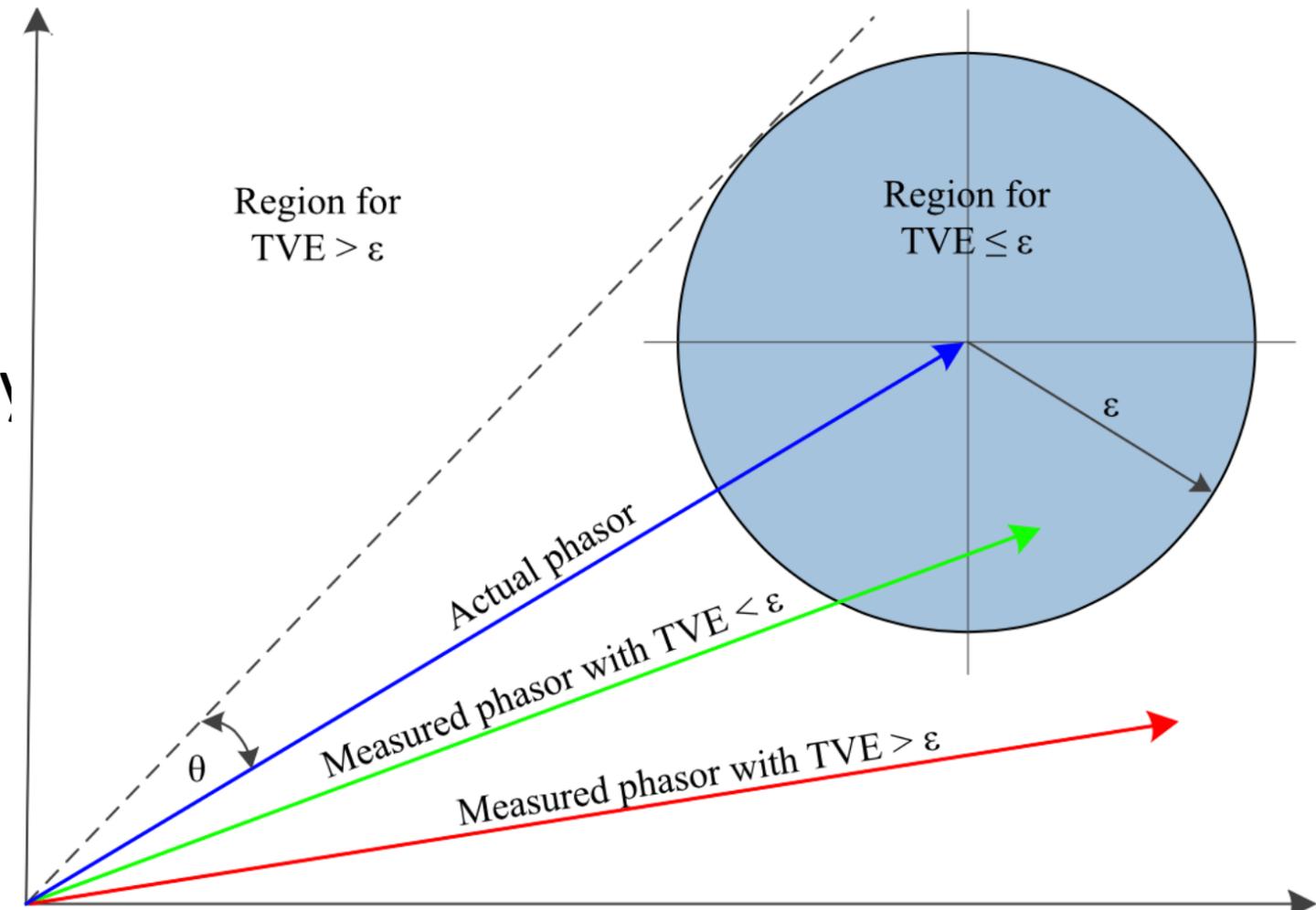
$$FE = |f_{true} - f_{measured}|$$

- 周波数変化率 (Rate of Change of Frequency)

$$RFE = \left| \left(\frac{df}{dt} \right)_{true} - \left(\frac{df}{dt} \right)_{measured} \right|$$

- 全ベクトルエラー

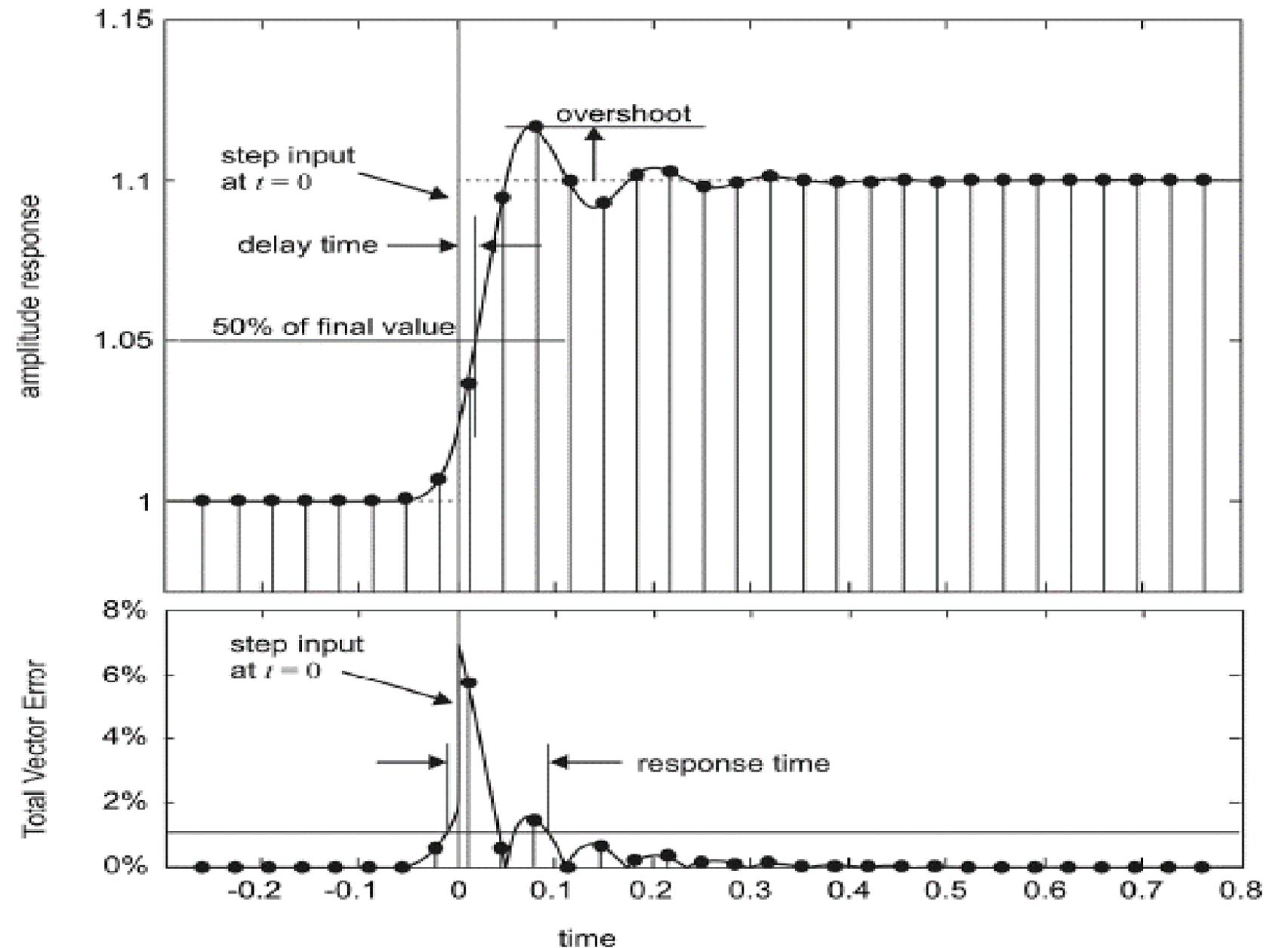
$$TVE = \sqrt{\frac{(\hat{X}_r - X_r)^2 + (\hat{X}_i - X_i)^2}{X_r^2 + X_i^2}}$$



測定精度の評価 - 基準

- 過渡試験と基準

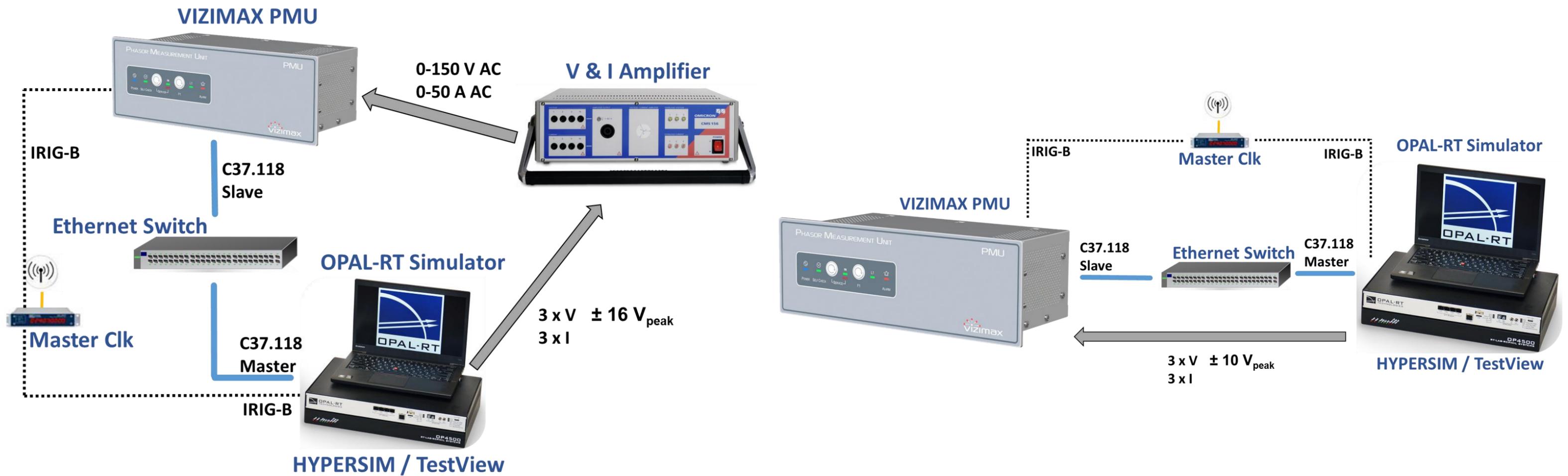
- Response Time
- Delay Time
- Overshoot and undershoot
- Latency



C37.118.1テスト規格

Test	Influence quantity	P Class Criteria	M Class Criteria
Signal Frequency Range	Signal frequency ±2Hz for P class ±5Hz for M class	TVE <1% FE <0.005Hz RFE <0.4Hz/s	TVE / FE / RFE <1% / <0.005Hz / <0.1Hz/s
Signal Magnitude (V/I)	Voltage magnitude 80% to 120% for P class 10% to 120% for M class Current magnitude 10% to 200%	TVE <1% FE<0.005Hz RFE<0.4Hz/s	TVE <1% FE<0.005Hz RFE<0.1Hz/s
Harmonic Distortion	2 nd to 50 th harmonic 1% for P class 10% for M class	TVE <1% FE<0.005Hz RFE<0.4Hz/s	TVE <1% FE<0.025Hz
Out-of-Band Interference	10Hz - f ₀ -F _s /2 and f ₀ +F _s /2 – 120Hz 10% for M class only	No requirement	TVE <1.3% FE<0.01Hz
Meas. BW Phase & Amp. Modulation	0.1Hz – min (F _s /10, 2) for P class 0.1Hz – min (F _s /5, 5) for M class	TVE <3% FE<0.003*Max Mod Freq RFE<0.18*pi*Max Mod Freq ²	TVE <3% FE<0.003*Max Mod Freq RFE<0.18*pi*Max Mod Freq ²
Frequency Ramp	±2Hz for P class ±5Hz for M class	TVE <1% FE<0.01Hz, RFE<0.4Hz/s	TVE <1% FE<0.01Hz, RFE<0.2Hz/s
Phase Step Change Magnitude Step Change	±10° ±10% of nominal magnitude	Delay time 1/(4*F _s) TVE response time 2/f ₀ Overshoot, undershoot 5% of step FE response time 4.5/f ₀ RFE response time 6/f ₀	Delay time 1/(4*F _s) TVE response time 7/F _s Overshoot, undershoot 10% of step FE response time max(14/f ₀ , 14/F _s) RFE response time max(14/f ₀ , 14/F _s)
Reporting latency	1000 consecutive reports	2/F _s	7/F _s

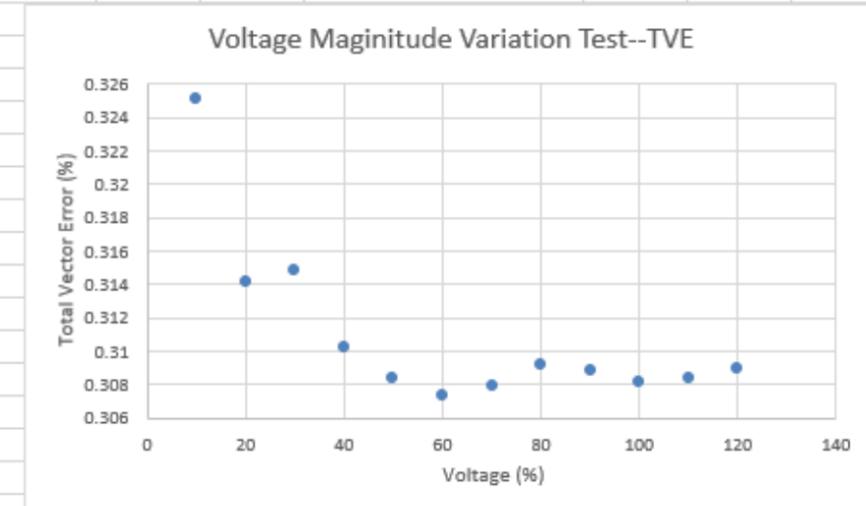
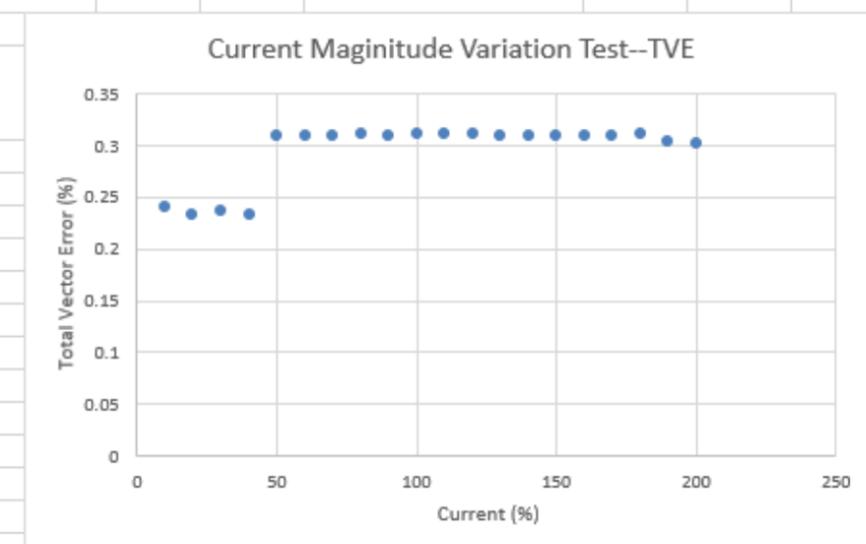
テストセットアップ



TestViewによる実装

- Excelからテストパラメータを読み込む
- テスト結果を事前にフォーマットされたExcelレポートにエクスポート

Client: OPAL-RT Technologies		By: OPAL01						
Proj #: RD_000_000		Approved: OPAL02						
Title: PMU Compliance Testing according to IEEE C37.118.1-2011								
Steady State Tests		Date: September 22, 2015						
Magnitude Variation Test								
	Nominal Voltage	Nominal current	Test voltage	Test current	TVE	FE	RFE	PASS/FAIL
	V	A	%	%	%	Hz	Hz/s	
1	69.28	5	100	10	0.2405	0.00023	0.01031	PASS
2	69.28	5	100	20	0.2328	0.00024	0.01126	PASS
3	69.28	5	100	30	0.2366	0.00024	0.01391	PASS
4	69.28	5	100	40	0.2327	0.00029	0.01505	PASS
5	69.28	5	100	50	0.3088	0.00022	0.01539	PASS
6	69.28	5	100	60	0.3092	0.00021	0.01308	PASS
7	69.28	5	100	70	0.3094	0.00023	0.01318	PASS
8	69.28	5	100	80	0.3115	0.00022	0.01265	PASS
9	69.28	5	100	90	0.3089	0.00028	0.01286	PASS
10	69.28	5	100	100	0.3102	0.0003	0.01039	PASS
11	69.28	5	100	110	0.3101	0.00026	0.01121	PASS
12	69.28	5	100	120	0.3115	0.00031	0.01372	PASS
13	69.28	5	100	130	0.309	0.00022	0.01029	PASS
14	69.28	5	100	140	0.3091	0.00034	0.01141	PASS
15	69.28	5	100	150	0.3082	0.00023	0.0137	PASS
16	69.28	5	100	160	0.3087	0.00026	0.01108	PASS
17	69.28	5	100	170	0.3083	0.00028	0.01778	PASS
18	69.28	5	100	180	0.3101	0.00027	0.01618	PASS
19	69.28	5	100	190	0.3032	0.00023	0.01438	PASS
20	69.28	5	100	200	0.3018	0.00021	0.01079	PASS
21	69.28	5	10	100	0.3251	0.00197	0.09719	PASS
22	69.28	5	20	100	0.3141	0.00107	0.06121	PASS
23	69.28	5	30	100	0.3149	0.00083	0.04596	PASS
24	69.28	5	40	100	0.3102	0.00044	0.0273	PASS
25	69.28	5	50	100	0.3084	0.00041	0.02064	PASS
26	69.28	5	60	100	0.3074	0.00032	0.01897	PASS
27	69.28	5	70	100	0.3079	0.00025	0.01553	PASS
28	69.28	5	80	100	0.3092	0.00027	0.0149	PASS



Vizimax PMUの事前認証



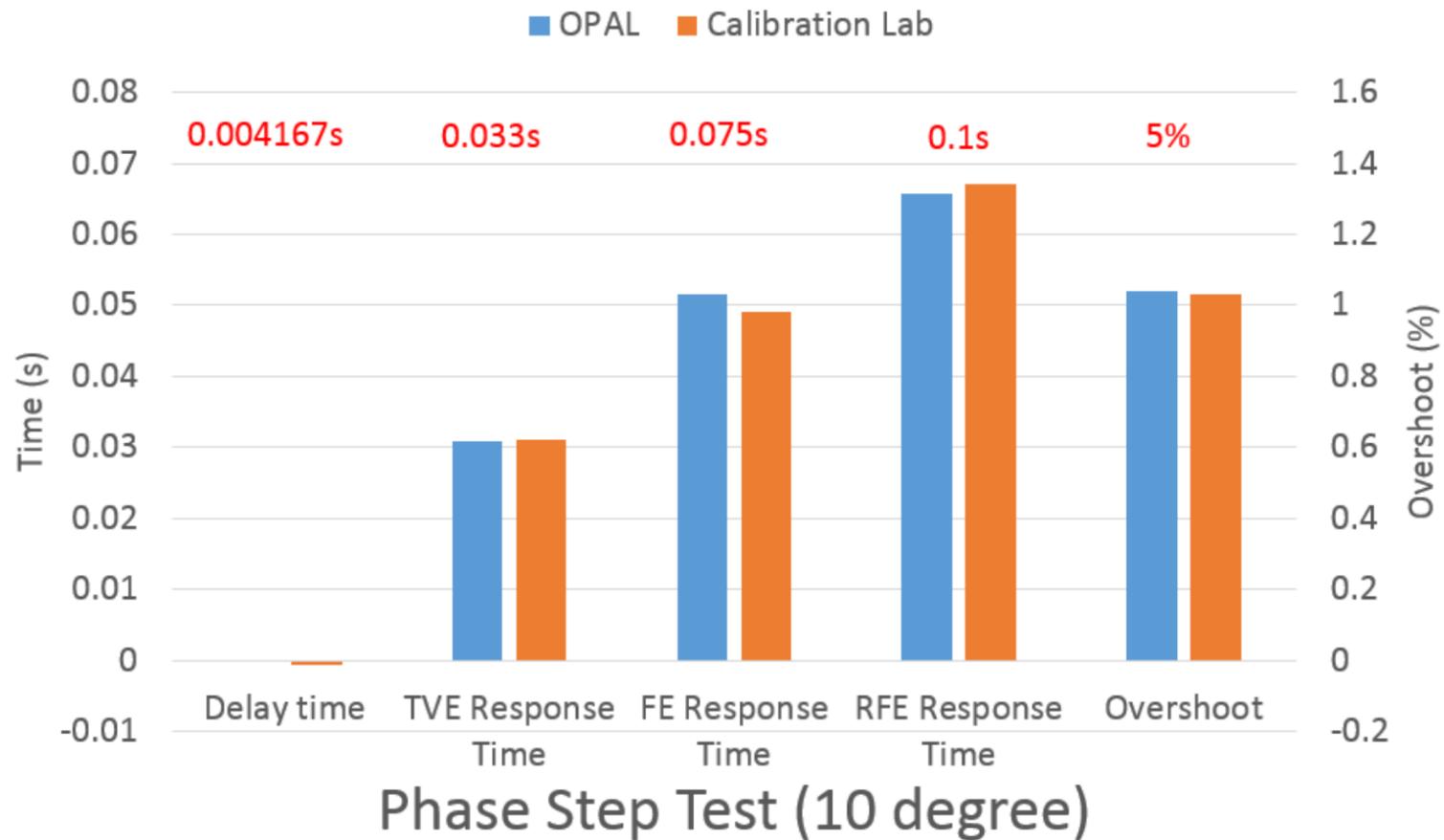
IEEE Conformity Assessment Program (ICAP)

Standard	IEEE C37.118.1a™-2014
Test Suite Specification	IEEE Synchrophasor Measurement Test Suite Specification, Version 2 - 2015

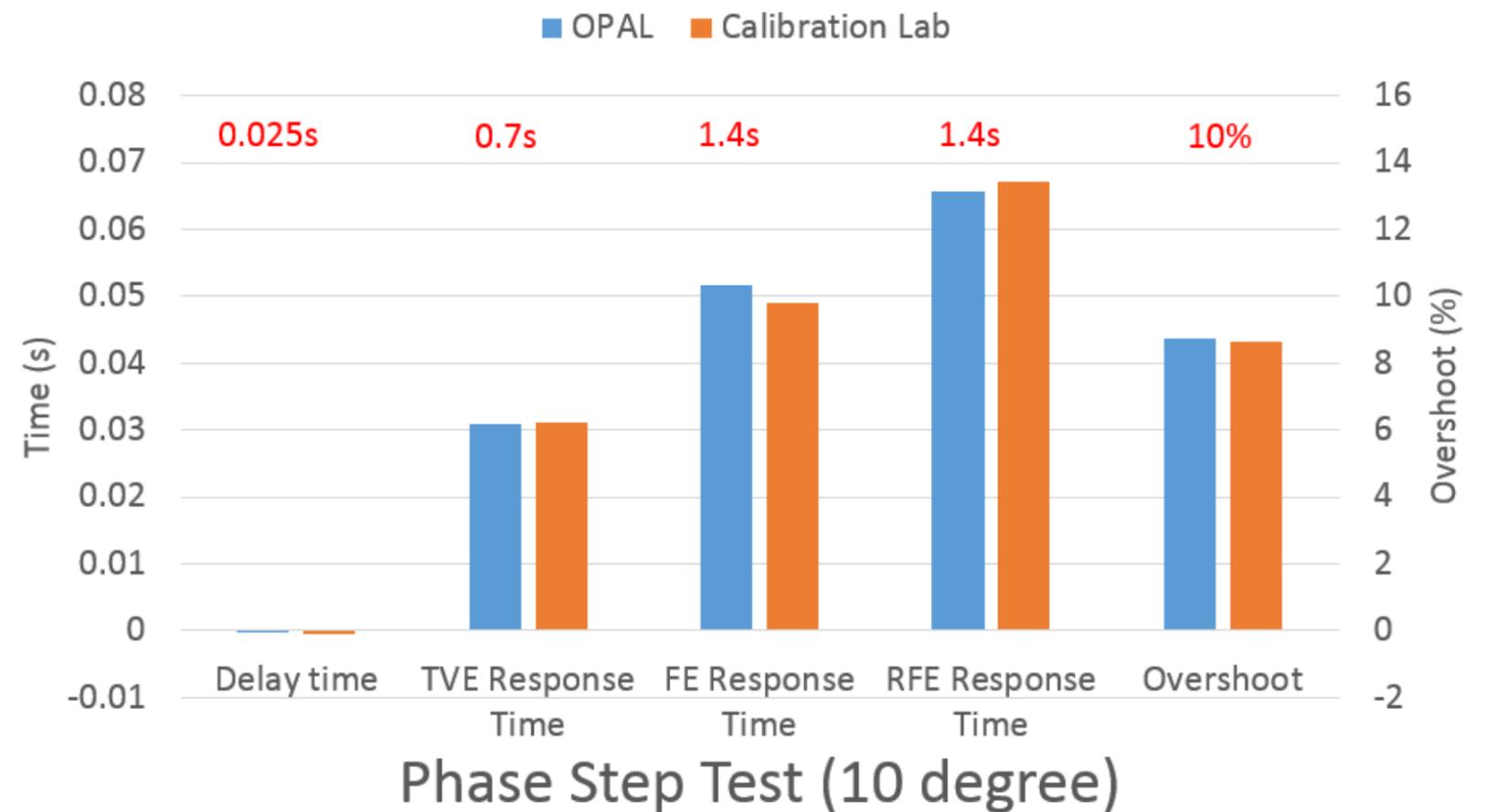
Company Logo	Applicant Name	Product Name	Model Number	Firmware Version
 SCHWEITZER ENGINEERING LABORATORIES	Schweitzer Engineering Laboratories, Inc.	Axion	SEL-2240	SEL-2241-R134-V1-Z001001-D21050417
	Siemens AG	SIPROTEC-5 PMU	6MD85 (50HZ Nominal Frequency)	V07.xx
	Vizimax	PMU 010000	RMEN35000	21997-1 v1.1.4.2

認証結果との比較 – ステップ変更テスト

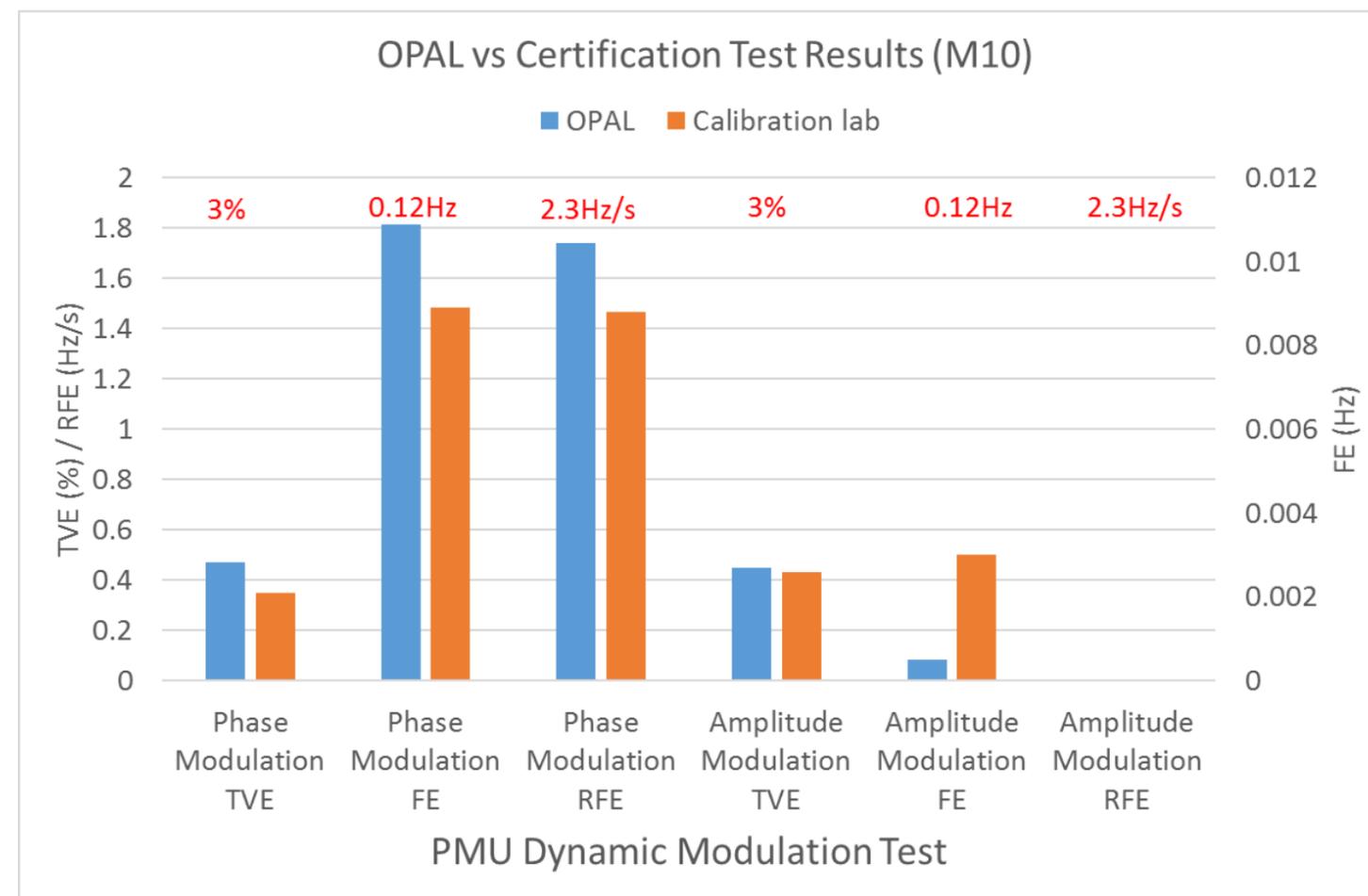
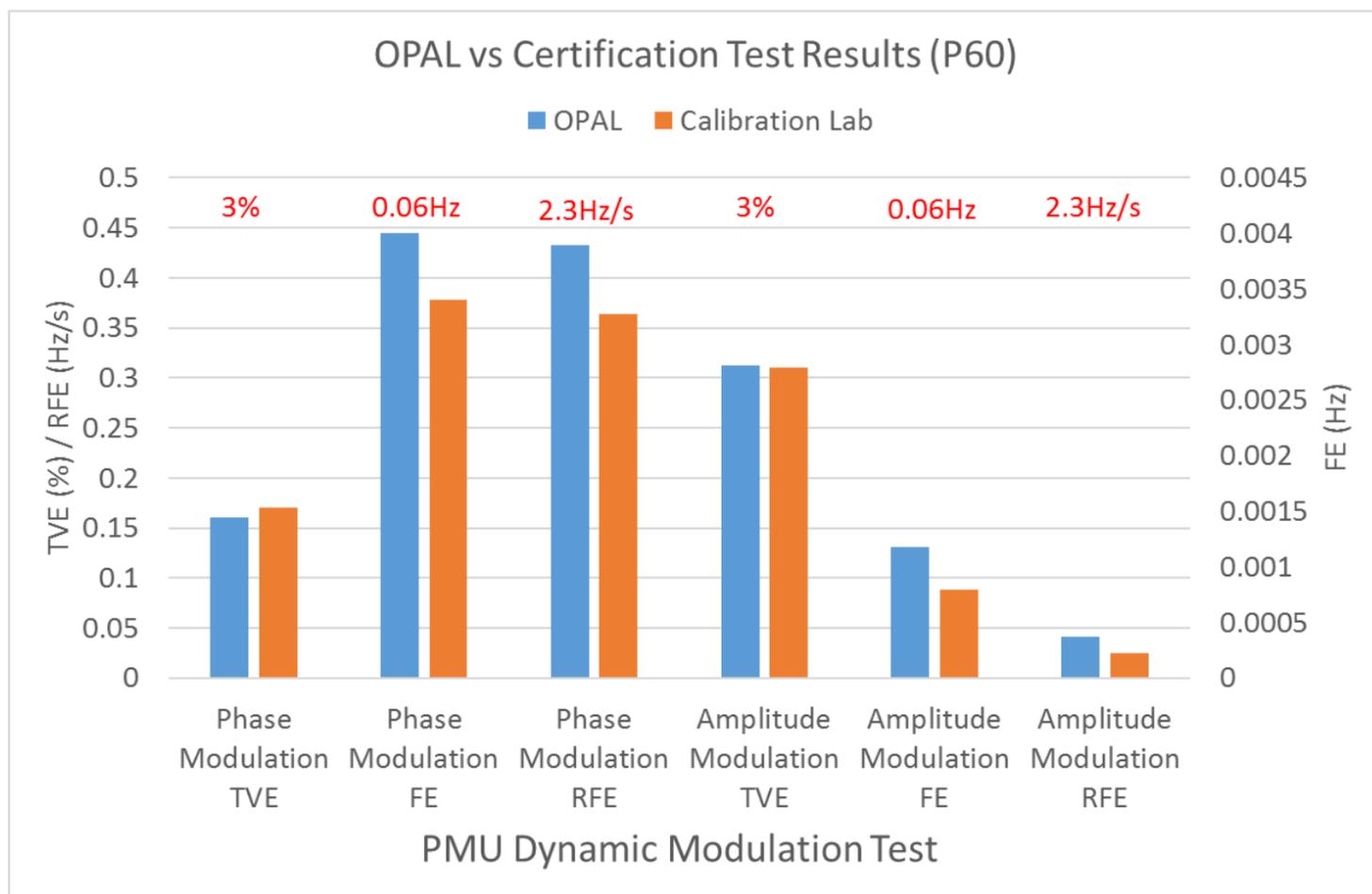
OPAL vs Certification Test Results (P60)

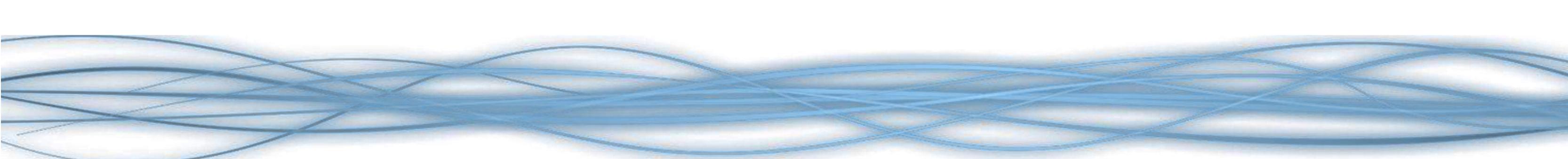


OPAL vs Certification Test Results (M10)



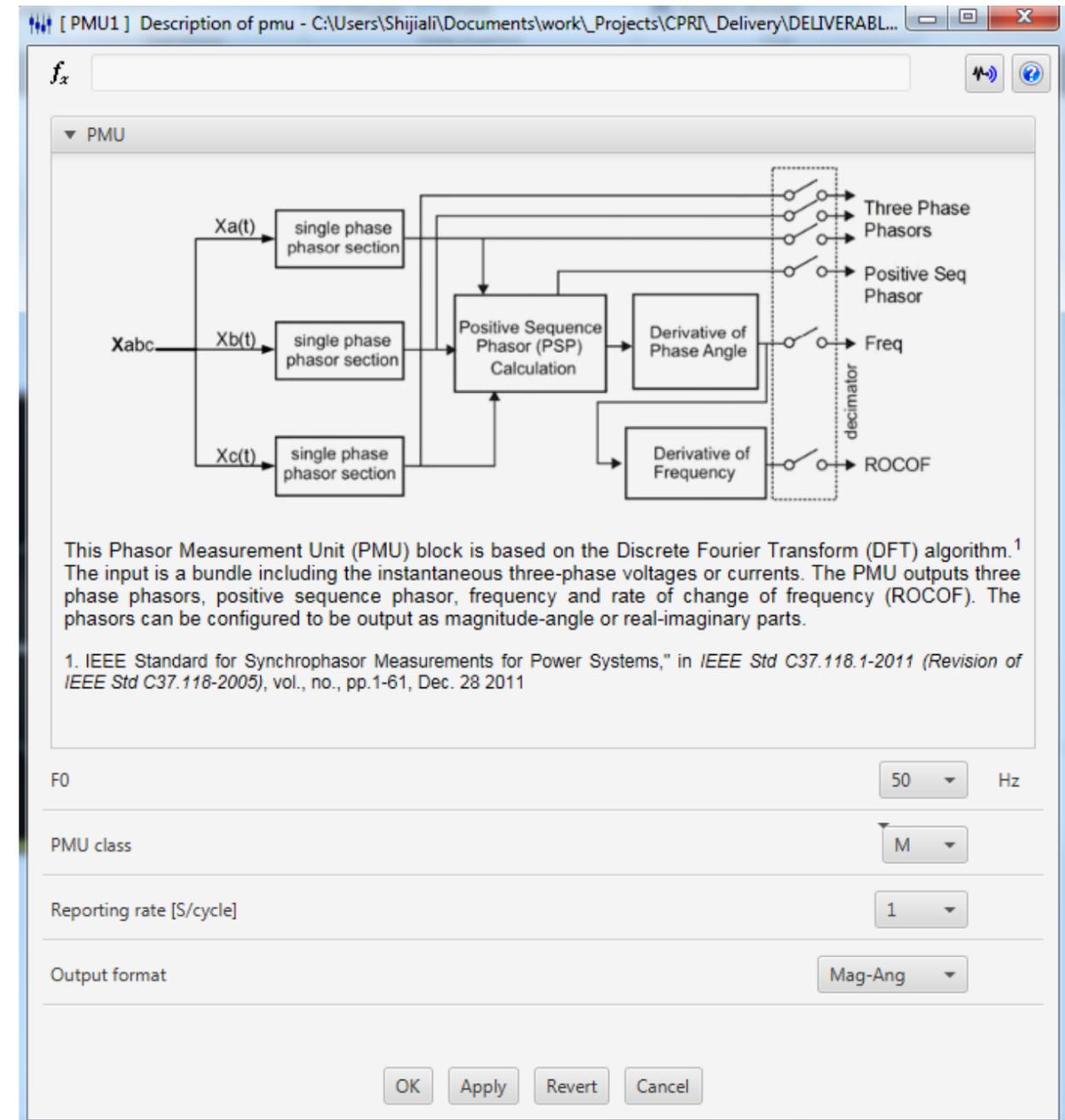
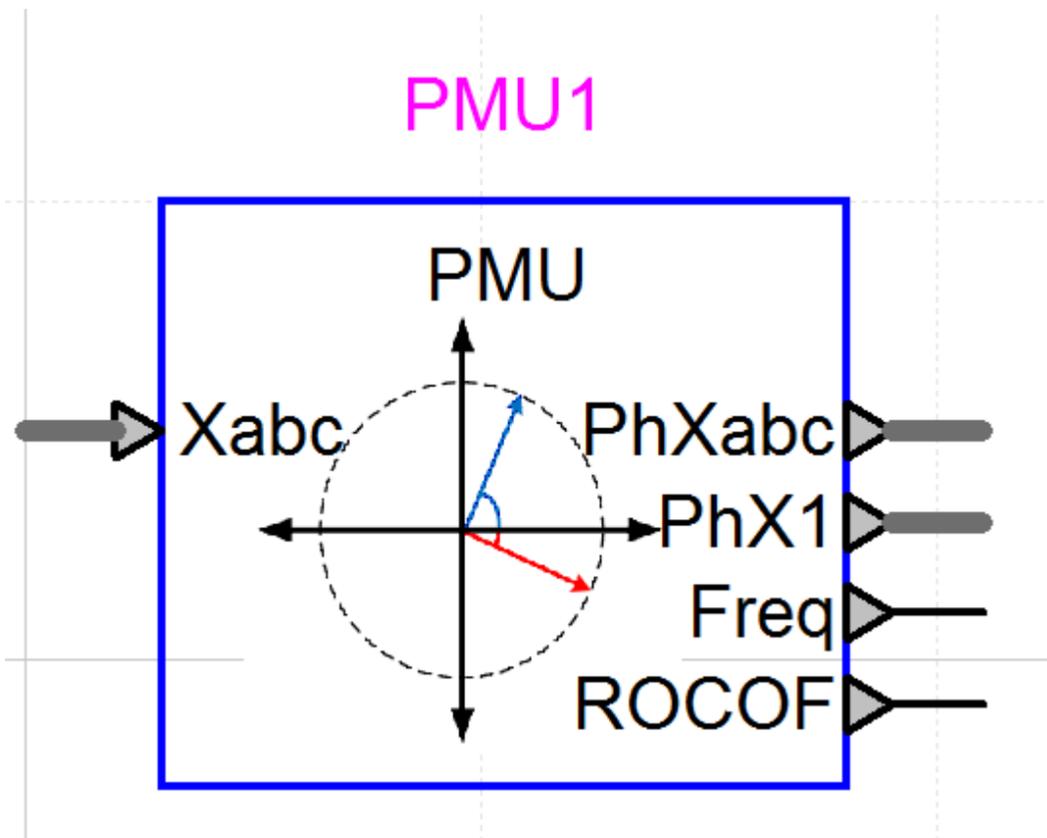
認証結果との比較 動的変調テスト



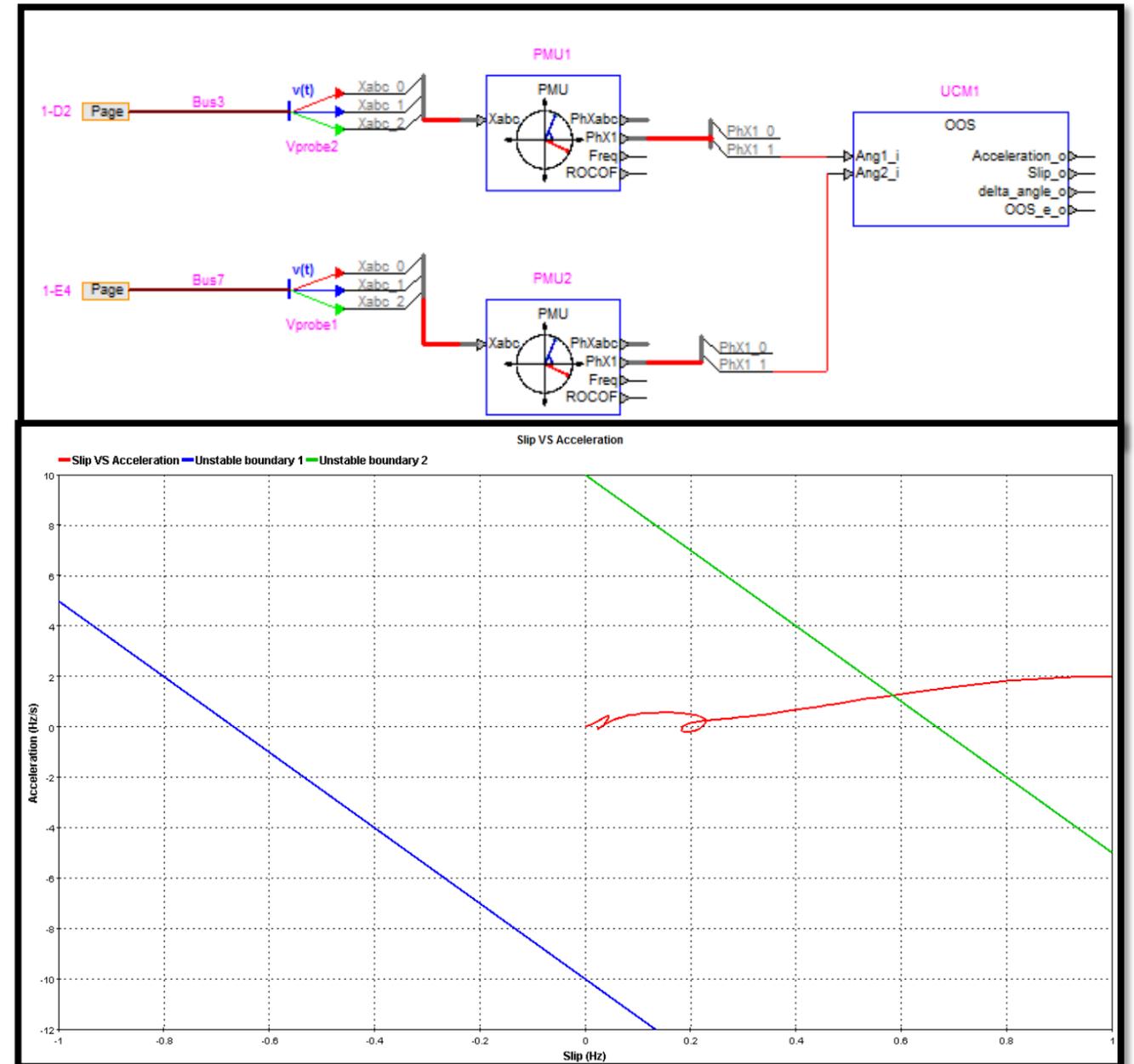
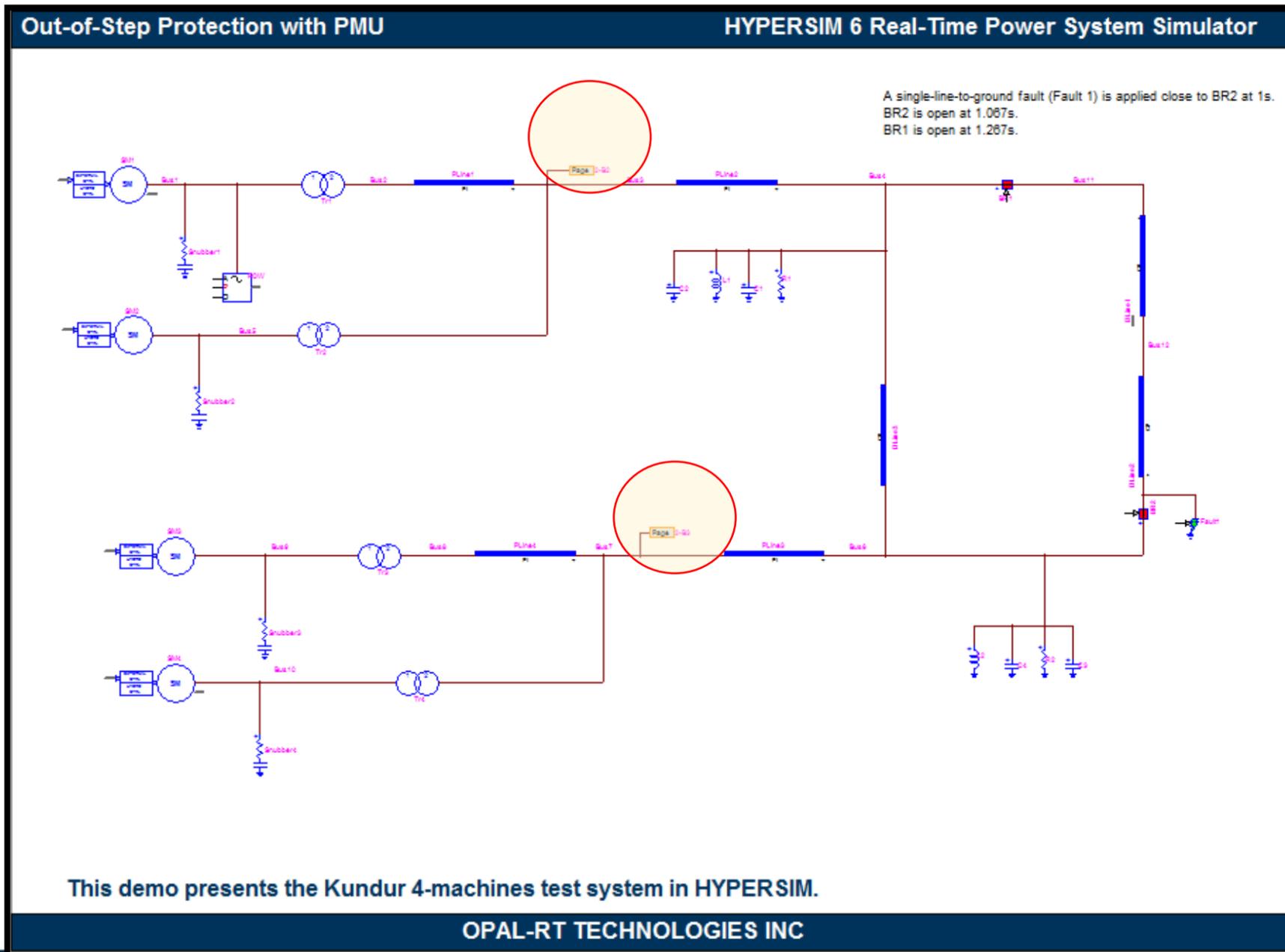


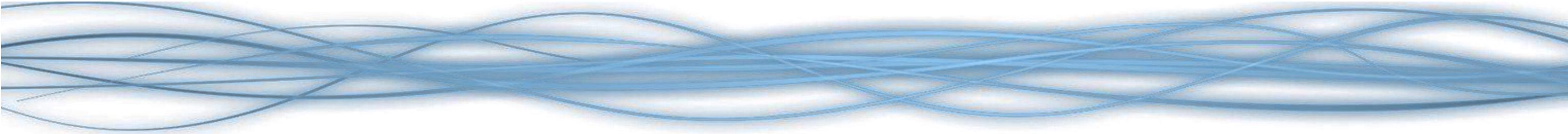
HYPERSIMで使われるモデル

- IEEE C37.118.1 – 2011 準拠



脱調検出の事例





OPAL-RT
TECHNOLOGIES