OPAL-RT TECHNOLOGIES

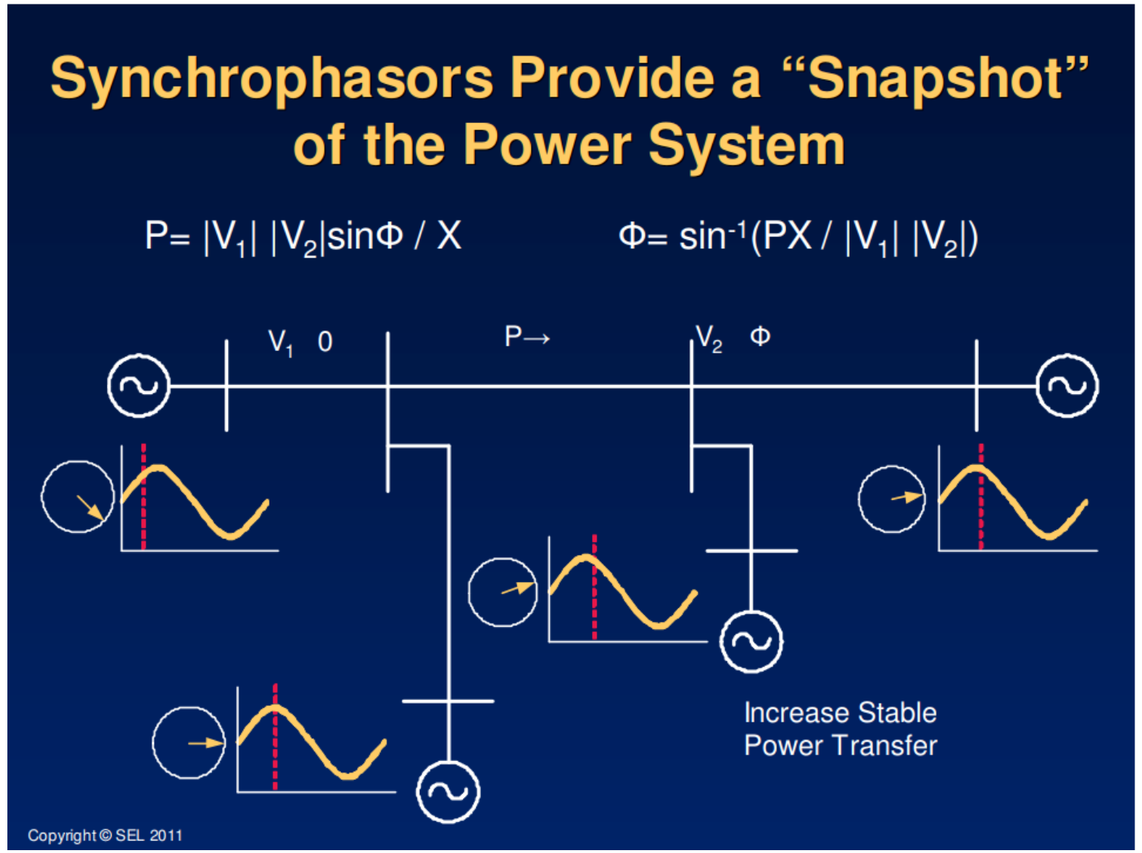
FROM IMAGINATION TO REAL-TIME

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。



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

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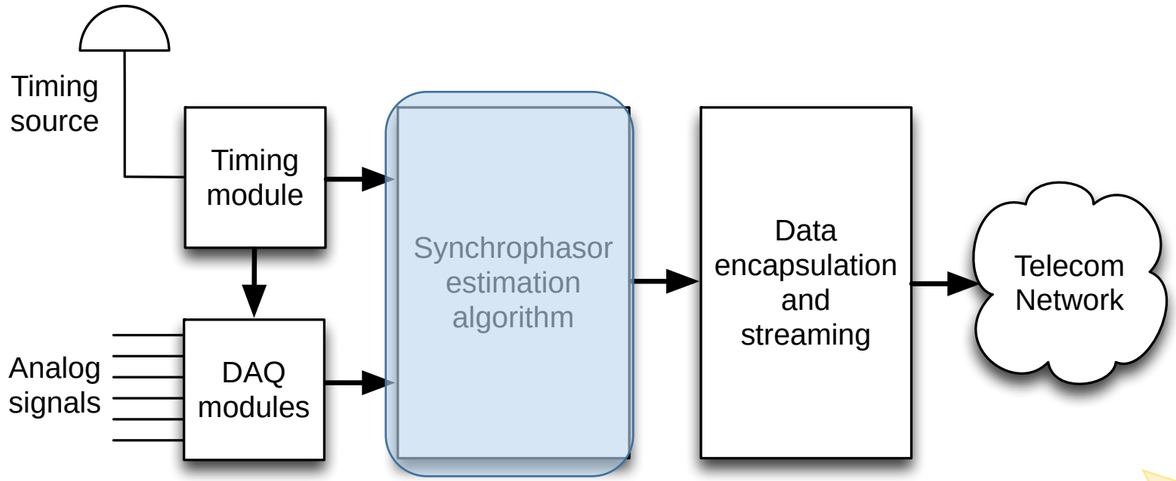
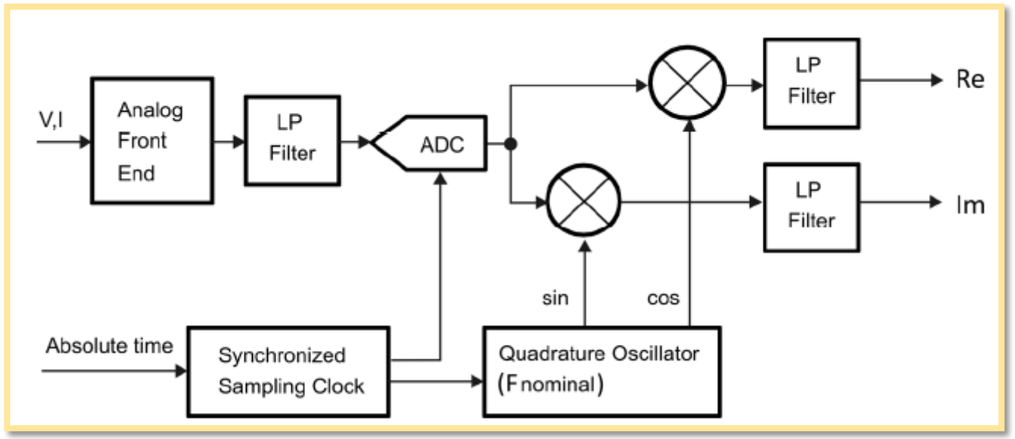
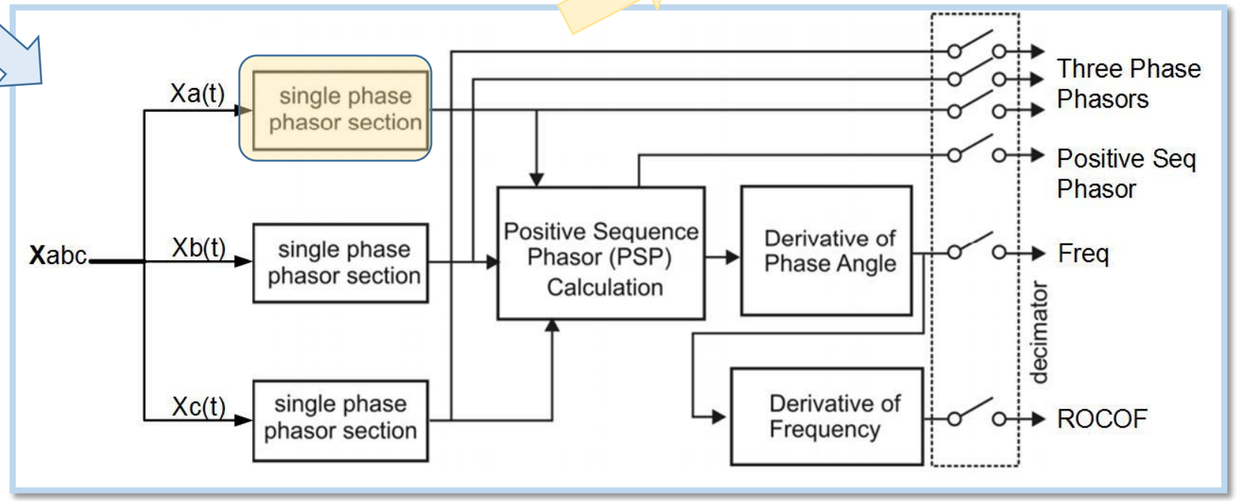
PMUの使用概念







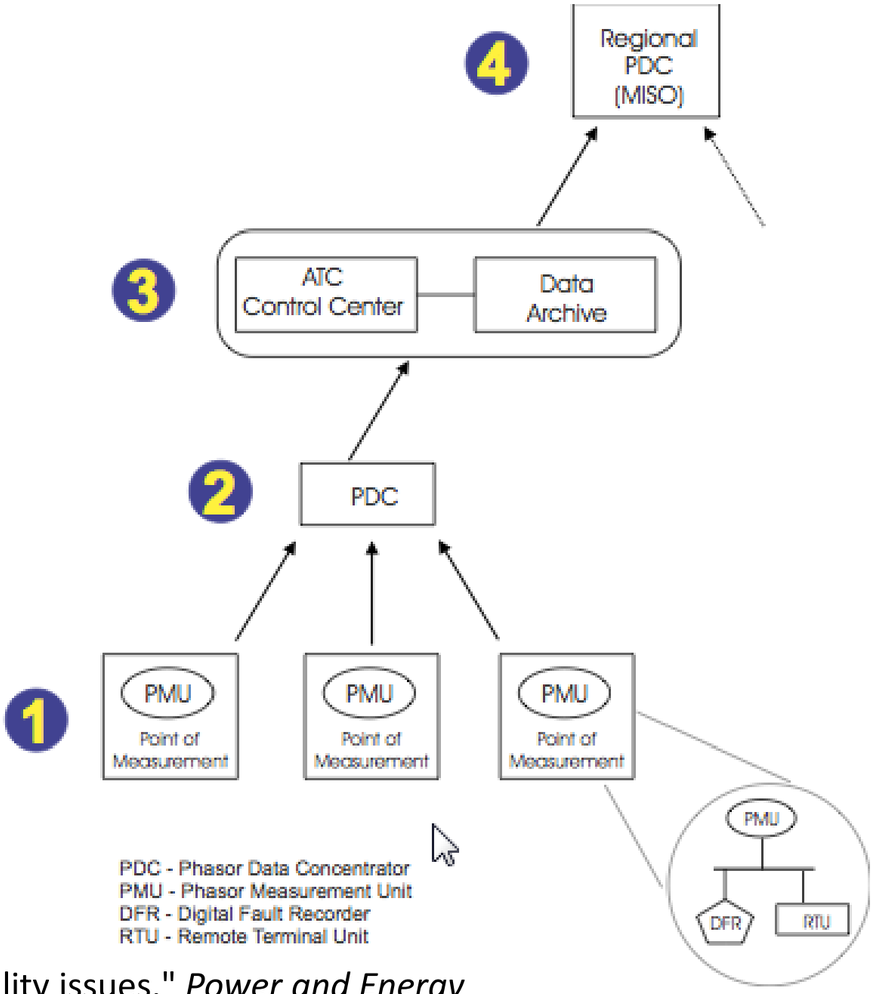
•Positive Sequence: A balanced three-phase system with the same phase sequence as the original sequence.

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、
  リアルタイムに出力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

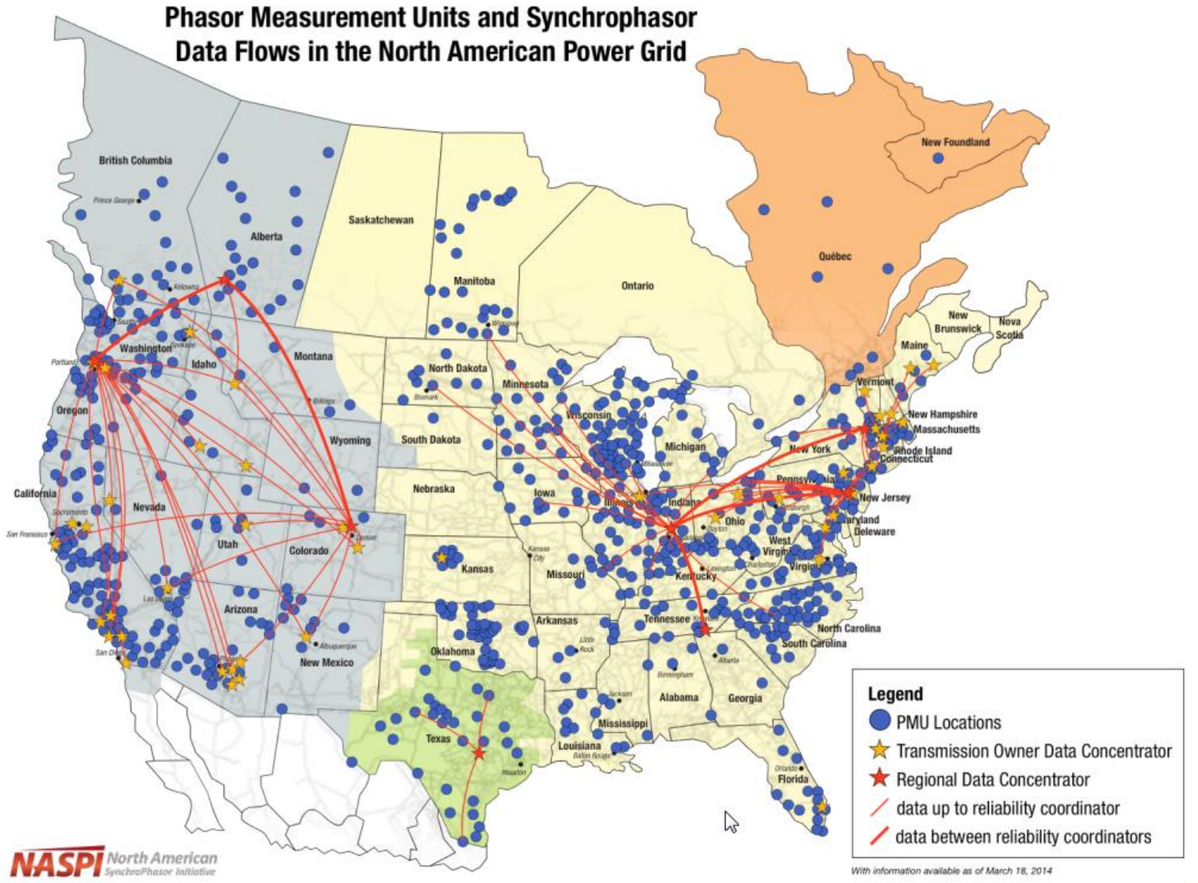
- https://www.naspi.org/
- http://openpdc.codeplex.com/

The Open Source Phasor Data Concentrator

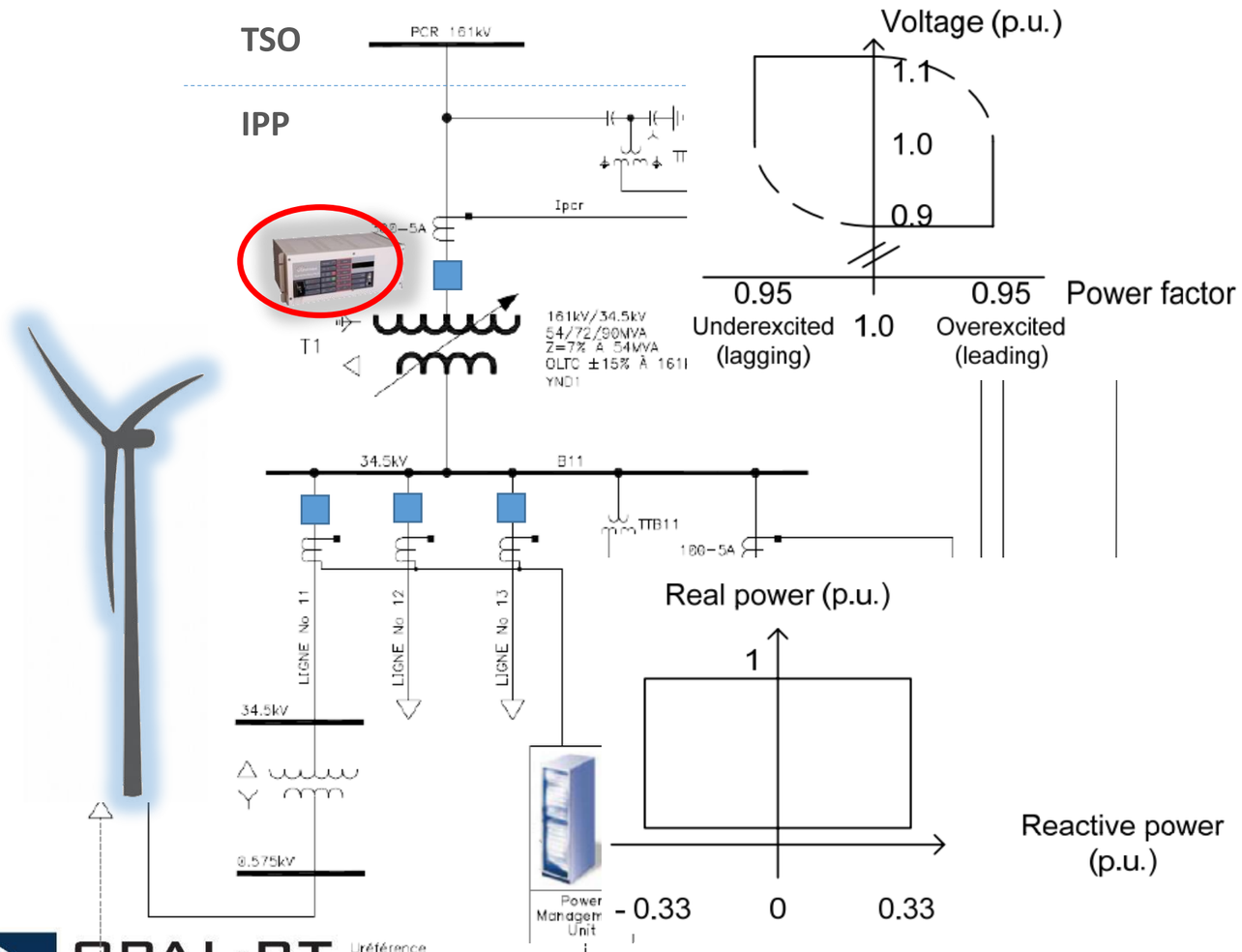
Kirihara, Kenta, et al. "Investigating synchrophasor data quality issues." *Power and Energy Conference at Illinois (PECI), 2014*. IEEE, 2014.

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

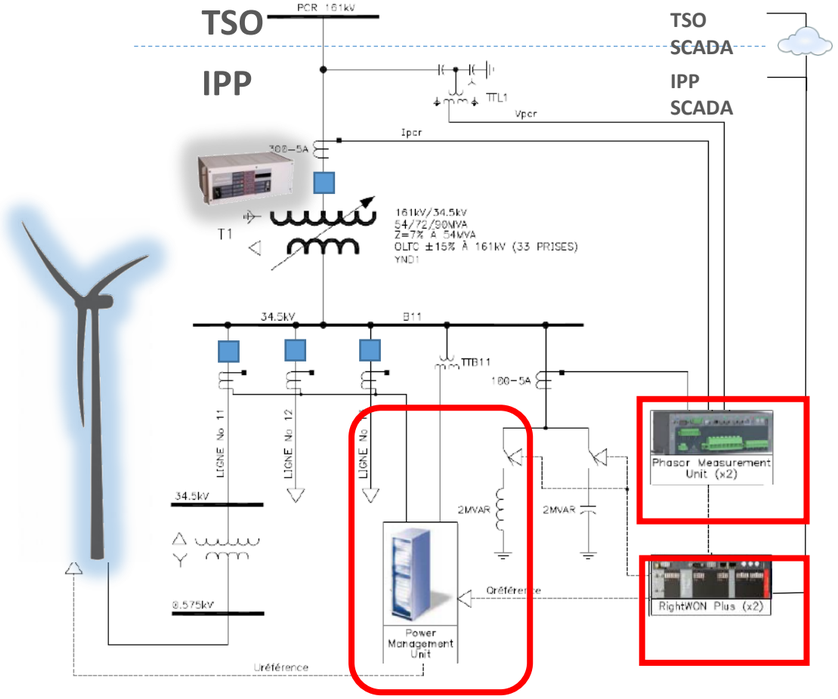


モデルベース設計– Mont-Rothery Wind Farm in Canada



- 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

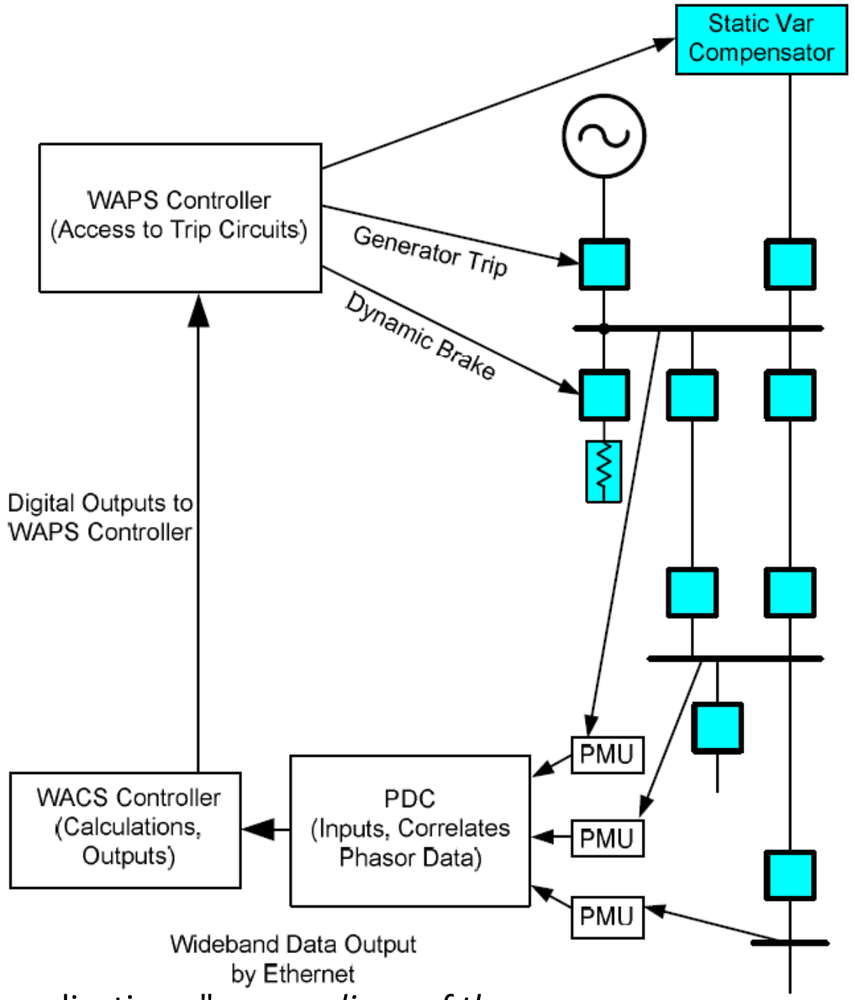
モデルベース設計– Mont-Rothery Wind Farm in Canada



- 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。



Schweitzer, Edmund O., et al. "Advanced real-time synchrophasor applications." *proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA*. 2008.

脱調検出

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

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

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

where:

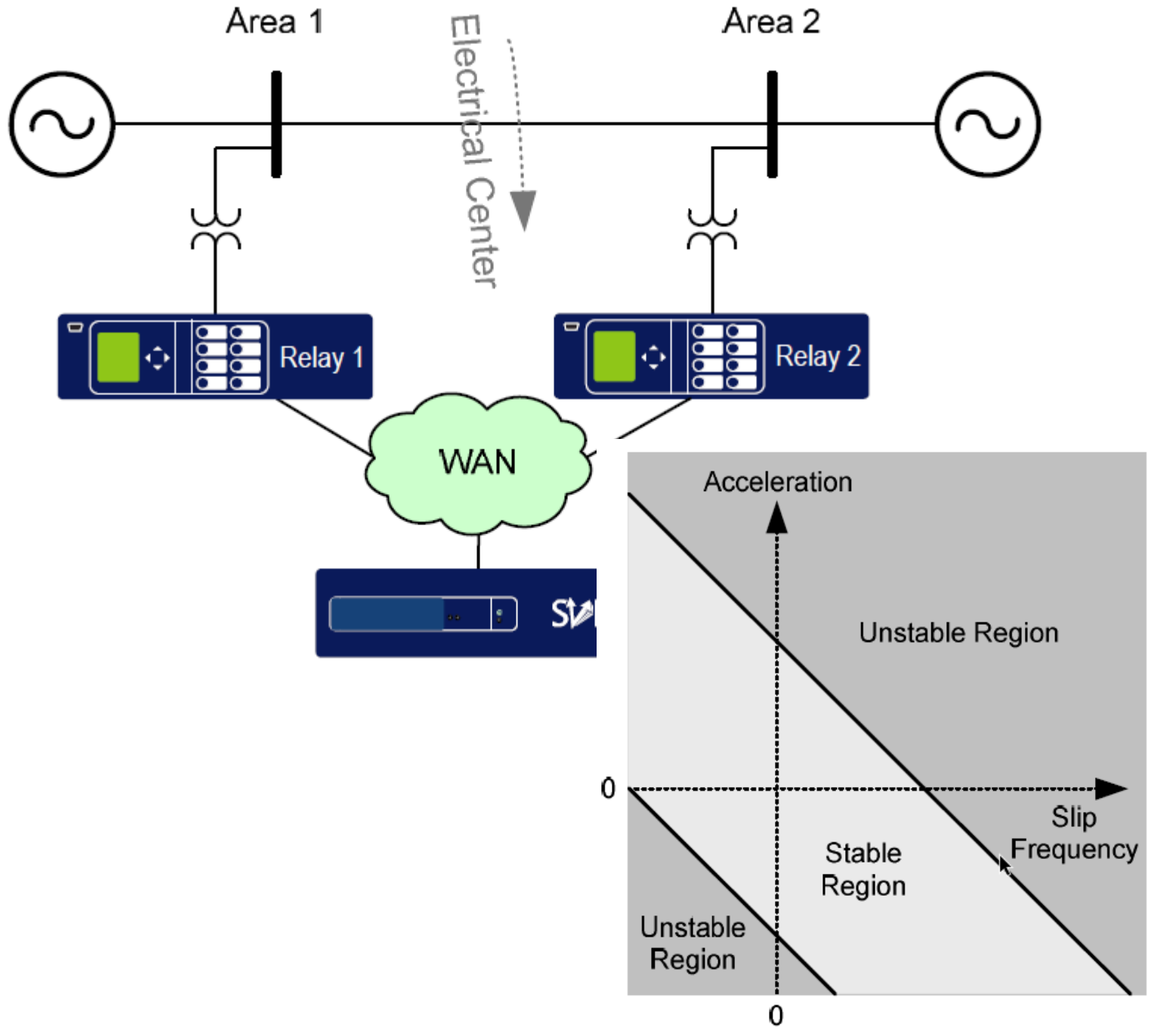
$V_{1\_Ang_k}^{Relay1}$ is the positive-sequence voltage angle of Relay 1 at the *k* processing interval

$V_{1\_Ang_k}^{Relay2}$ 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

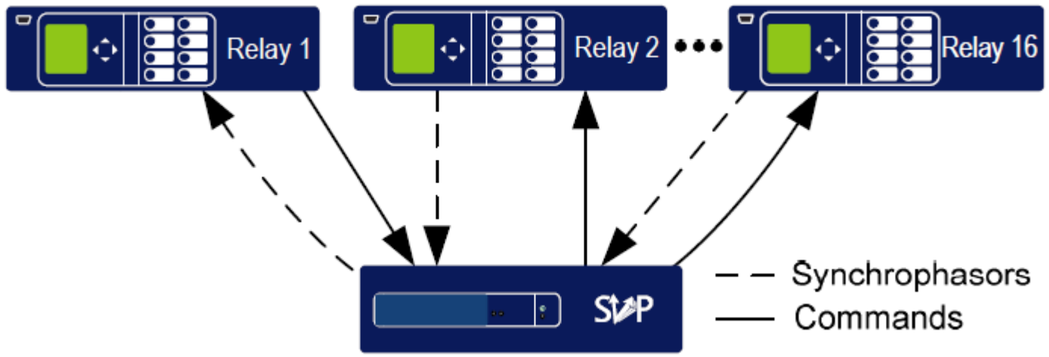
A_{fk} is the acceleration at the *k* processing interval

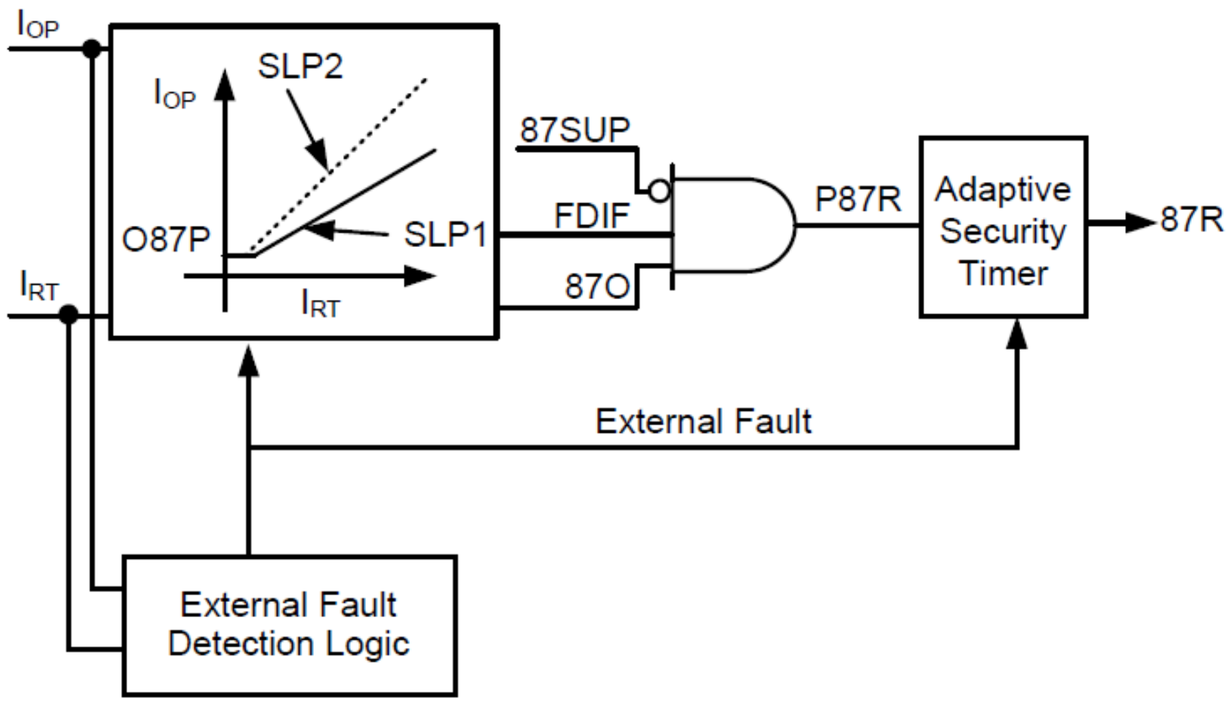
MRATE is the synchrophasor message rate



Schweitzer, Edmund O., et al. "Advanced real-time synchrophasor applications." *proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA*. 2008.

分散母線差動保護





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

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

Schweitzer, Edmund O., et al. "Advanced real-time synchrophasor applications." *proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA*. 2008.

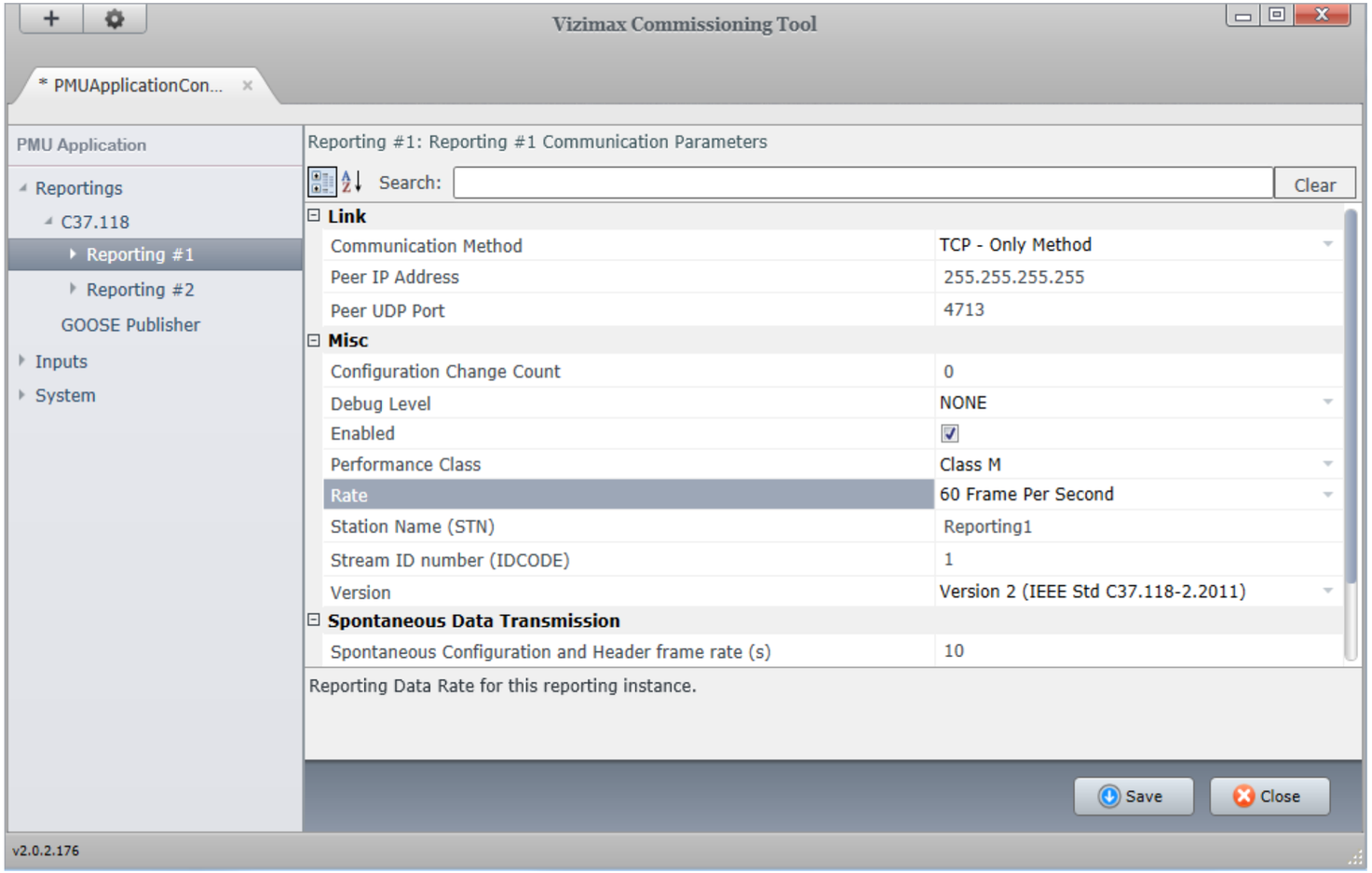
PMUの認識

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

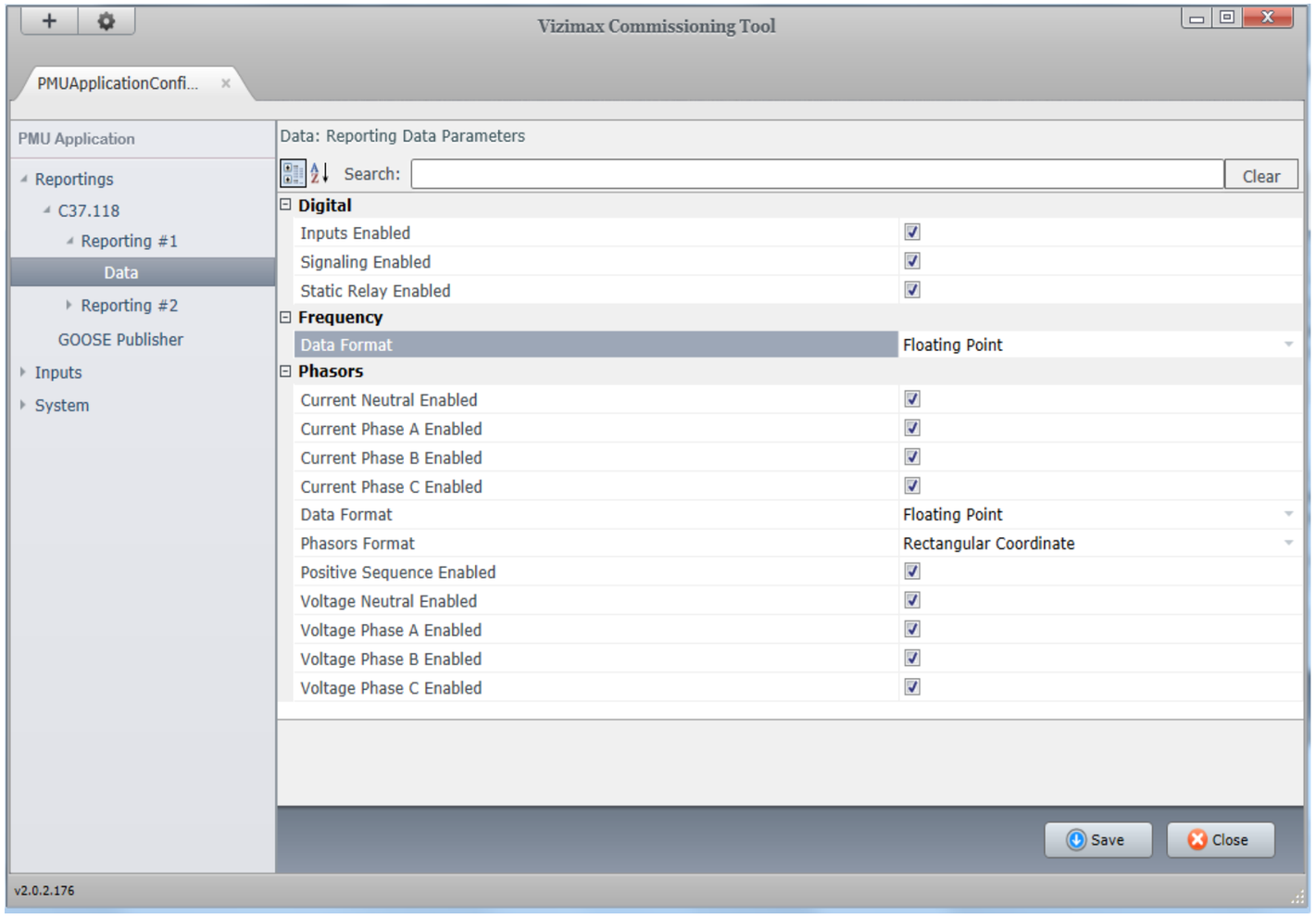


Peer IP address: 設定情報を受信した無線コントローラーのIPアドレス。

Vizimax PMU 構成

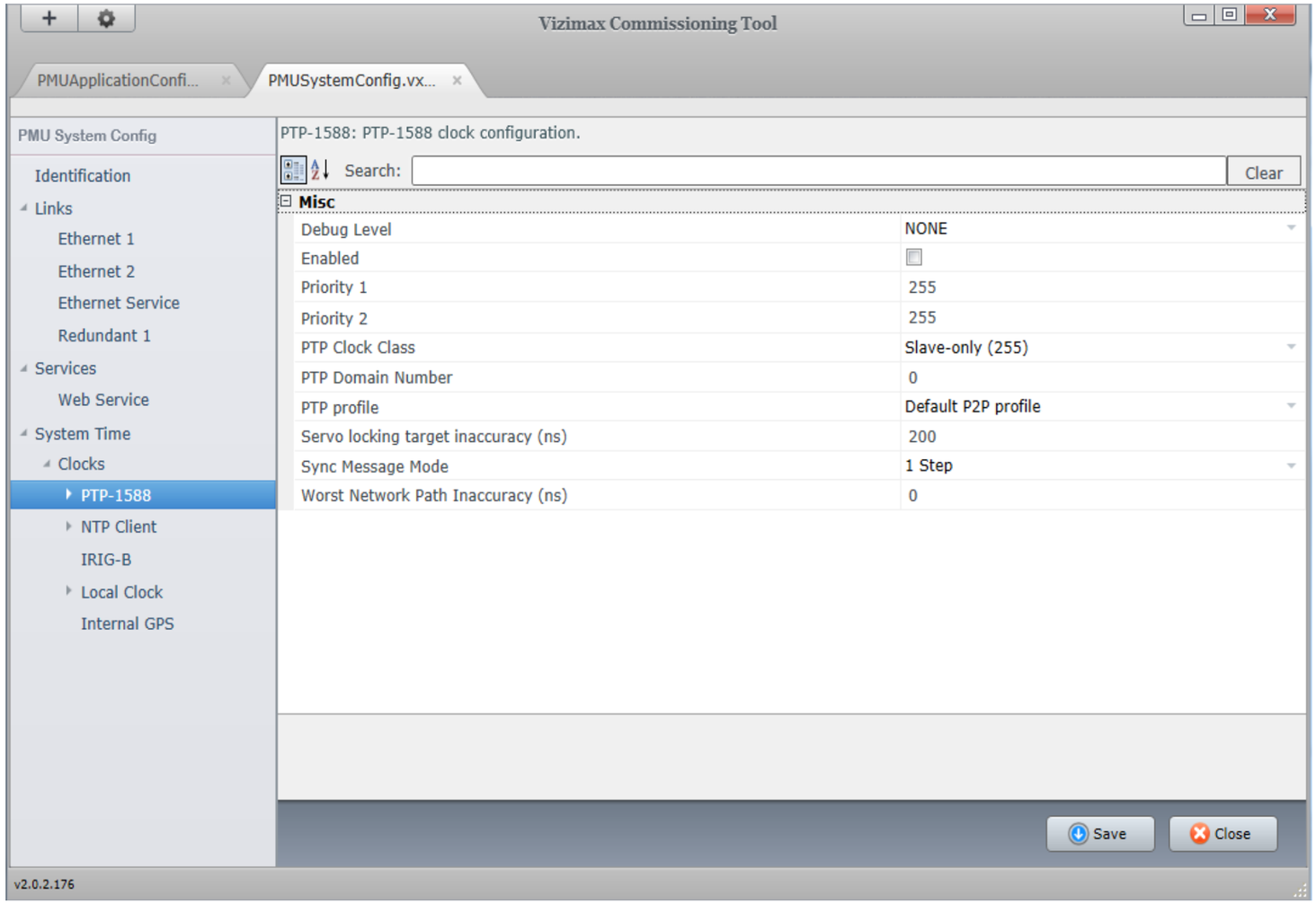
- PMUストリームに含めるデータを選択

  位相
  - 矩形
  - 極性



Vizimax PMU 構成

- 時刻同期
  - PTP – 1588
  - IRIG-B
  - PPS



RTSとPMUの接続

C37.118 Master configuration

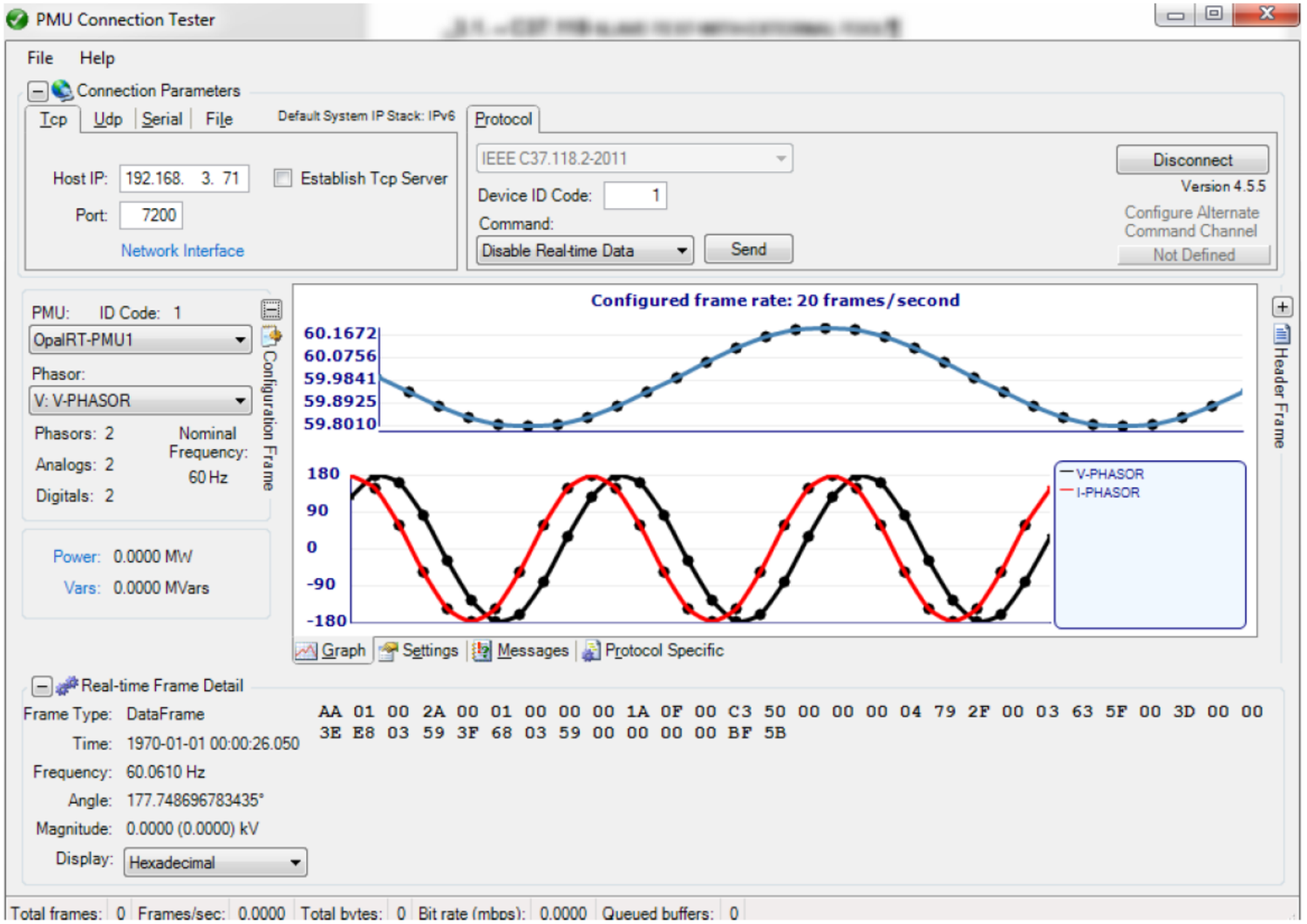
- .OPAL and .IO

```
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

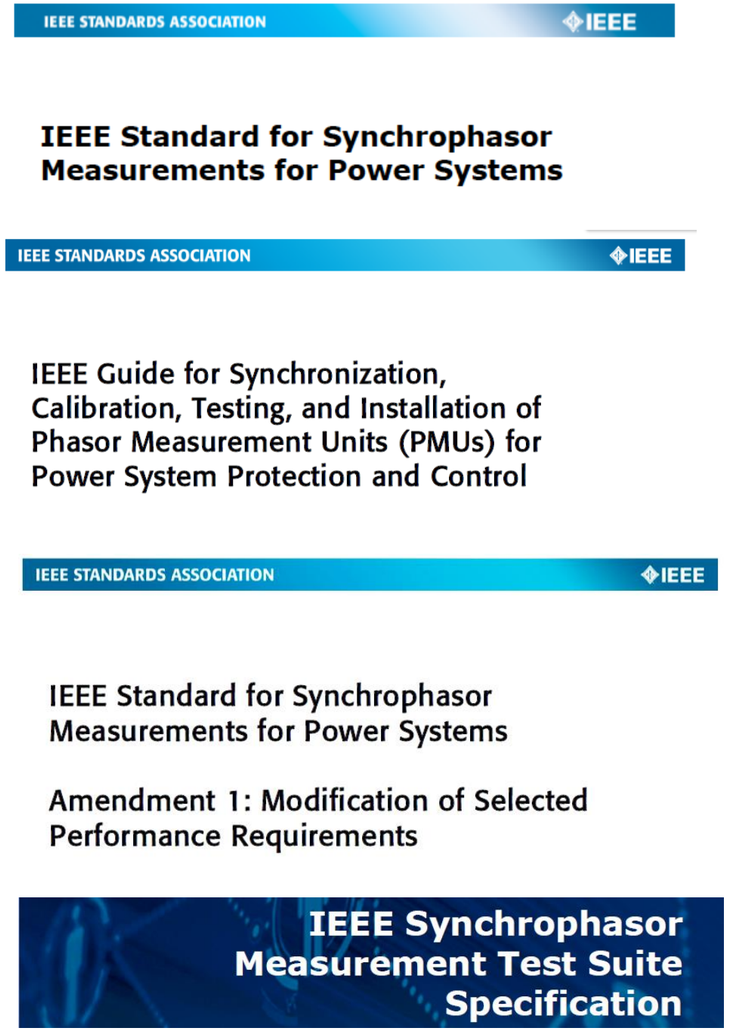
- Tcp
- Host IP
- Port number
- Device ID
- Settings - ForceIPv4 - True



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



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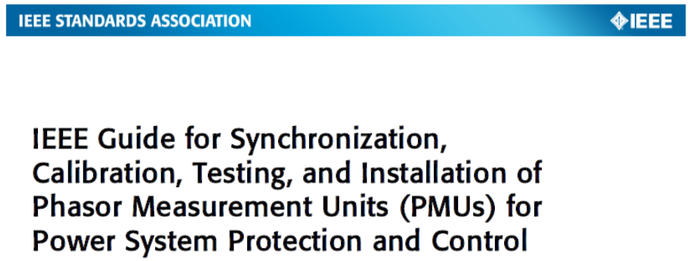
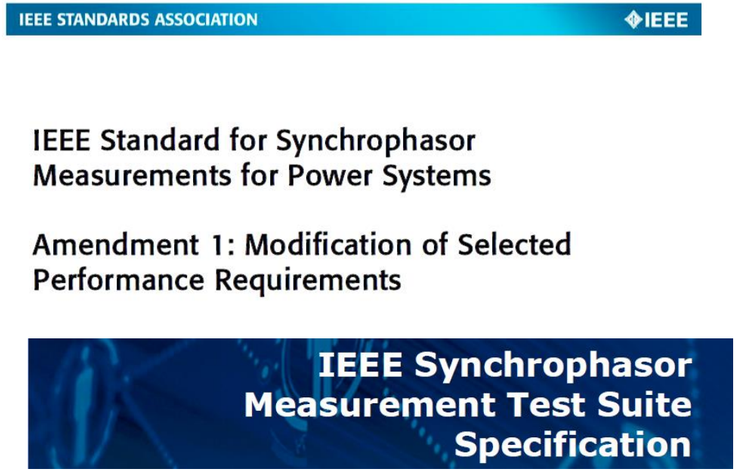
A Glance at the IEEE Std. C37.118.1

- 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





OPAL-RT TECHNOLOGIES

測定精度の評価-基準

- 定常状態テスト基準
  - 周波数エラー

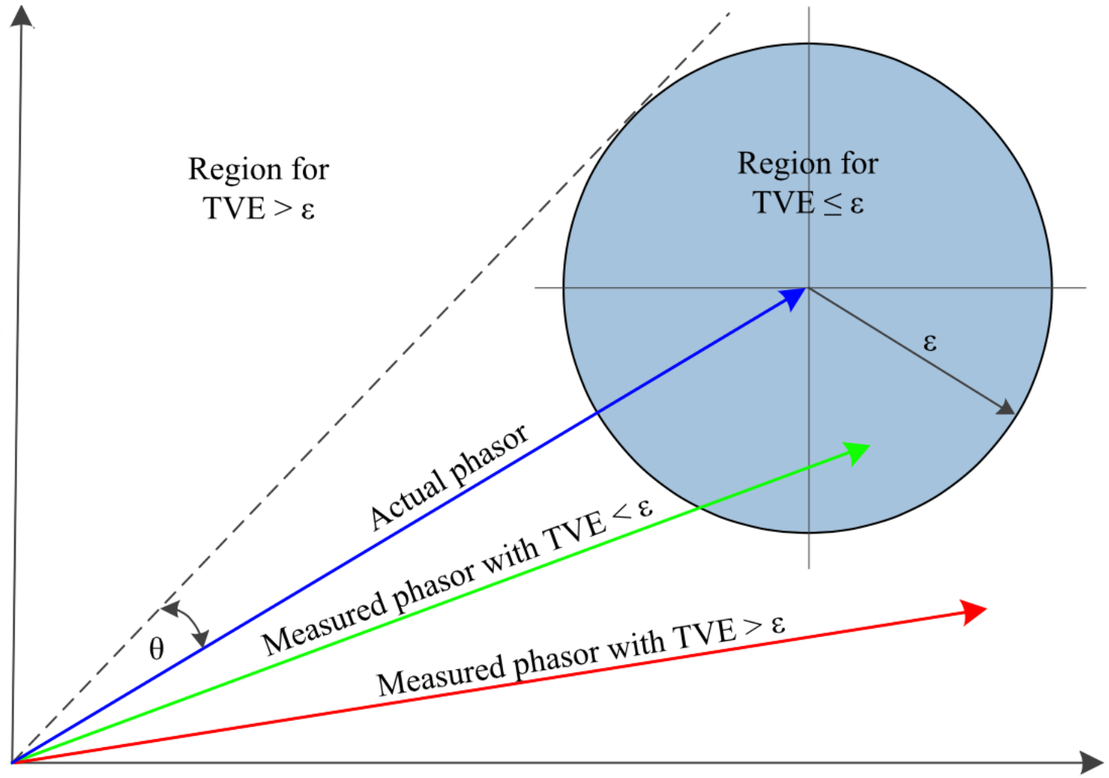
$$\mathrm{FE} = \left| f_{true} - f_{measured} \right|$$

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

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

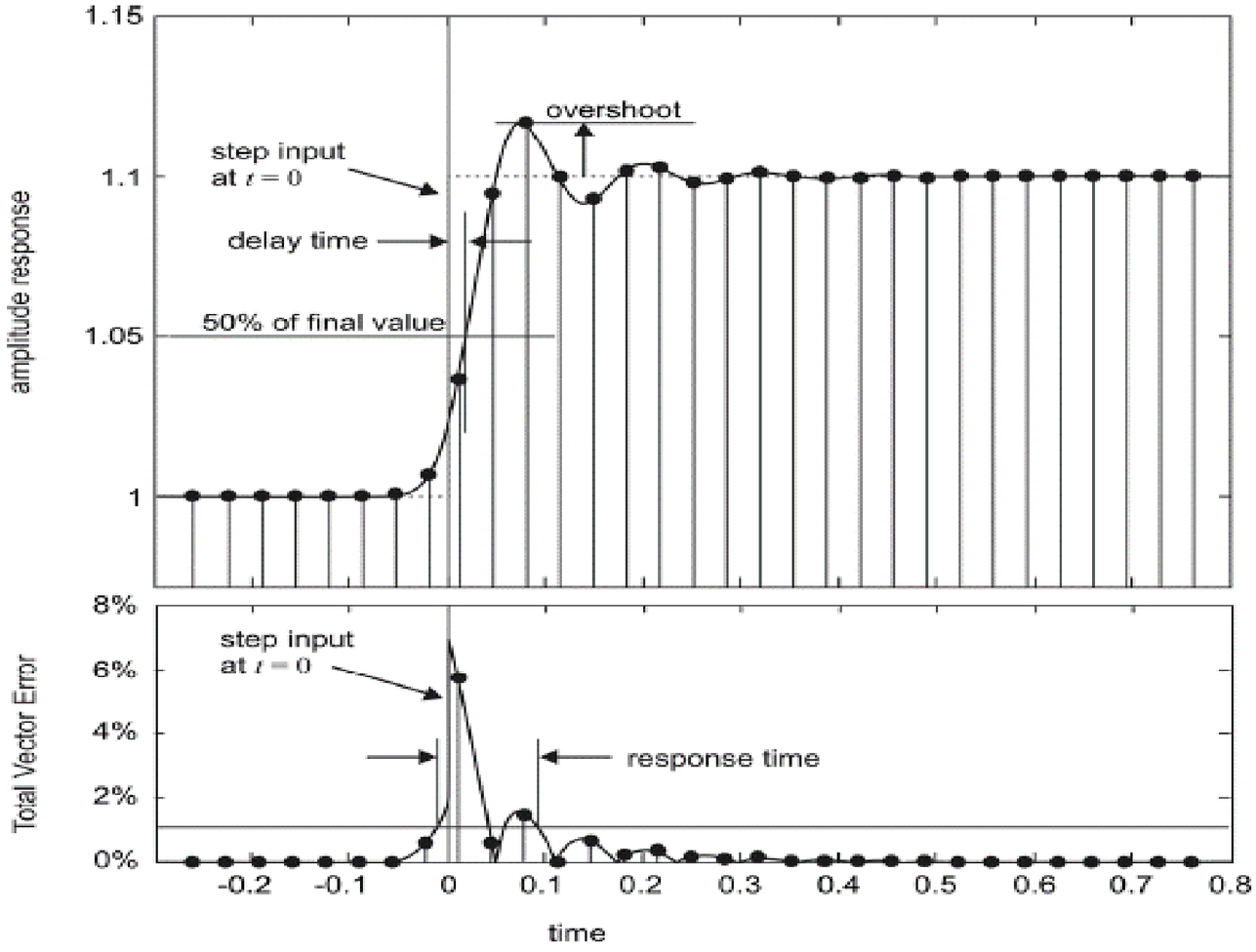
  - 全ベクトルエラー

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



測定精度の評価　-基準

- 過渡試験と基準
  - Response Time
  - Delay Time
  - Overshoot and undershoot
  - Latency



OPAL-RT TECHNOLOGIES

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 - f0-Fs/2 and f0+Fs/2 – 120Hz 10% for M class only	No requirement	TVE <1.3% FE<0.01Hz
Meas. BW **Phase & Amp. Modulation**	0.1Hz – min (Fs/10, 2) for P class 0.1Hz – min (Fs/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*Fs) TVE response time 2/f0 Overshoot, undershoot 5% of step FE response time 4.5/f0 RFE response time 6/f0	Delay time 1/(4*Fs) TVE response time 7/Fs Overshoot, undershoot 10% of step FE response time max(14/f0, 14/Fs) RFE response time max(14/f0, 14/Fs)
Reporting latency	1000 consecutive reports	2/Fs	7/Fs

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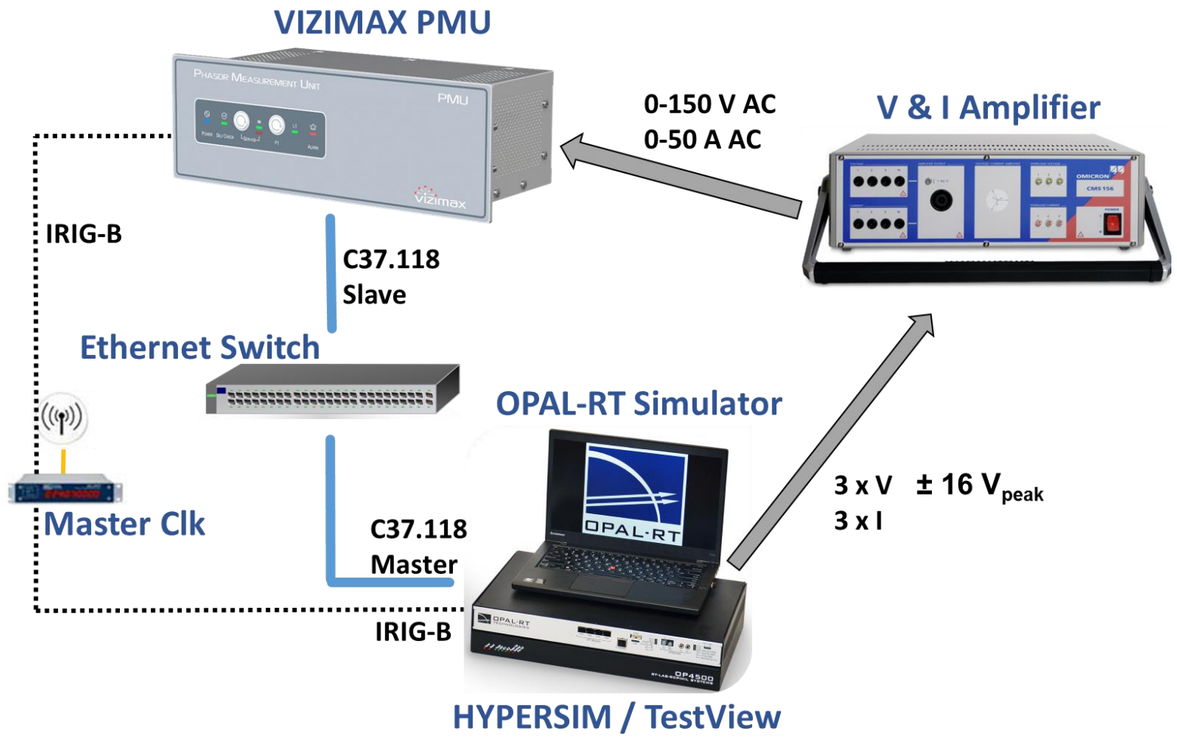
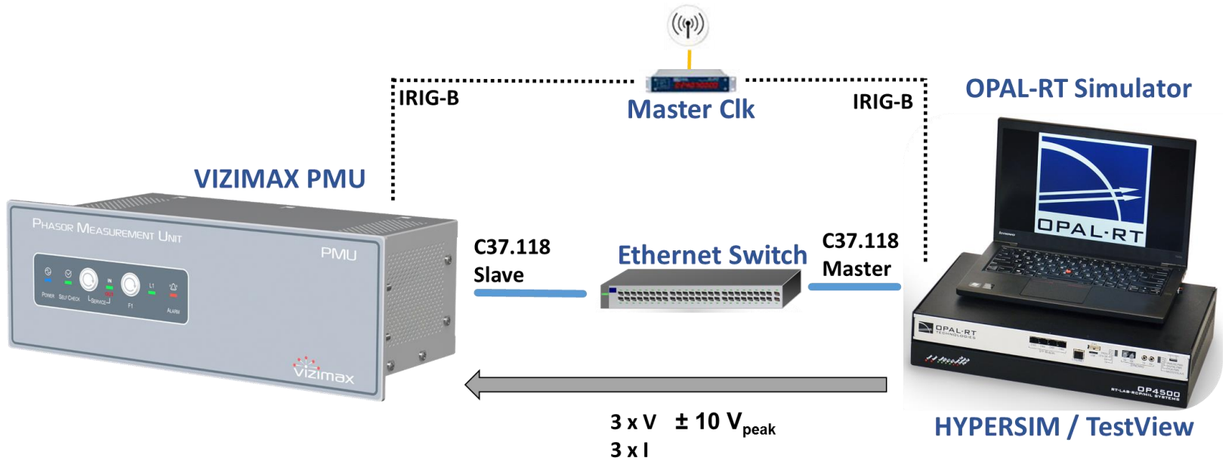
テストセットアップ





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TestViewによる実装

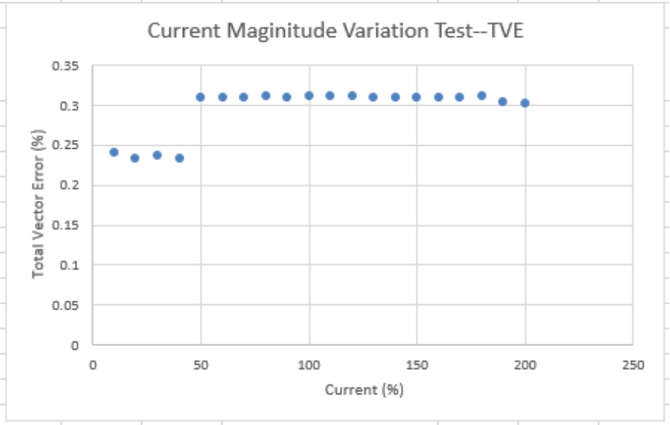
- Excelからテストパラメーターを読み込む
- テスト結果を事前にフォーマットされたExcelレポートにエクスポート

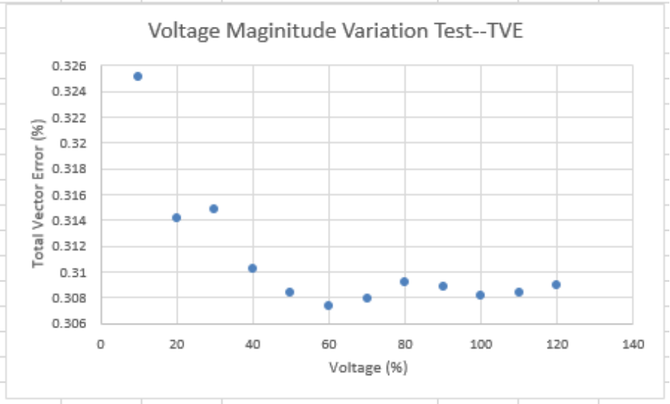
Client: OPAL-RT Technologies
Proj #: RD_000_000
Title: PMU Compliance Testing according to IEEE C37.118.1-2011
Steady State Tests

By: OPAL01
Approved: OPAL02
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





OPAL-RT TECHNOLOGIES

Vizimax PMUの事前認証

vizimax
ENERGY 3.0

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
SEL SCHWEITZER ENGINEERING LABORATORIES	Schweitzer Engineering Laboratories, Inc.	Axion	SEL-2240	SEL-2241-R134-V1-Z001001-D21050417
SIEMENS	Siemens AG	SIPROTEC-5 PMU	6MD85 (50HZ Nominal Frequency)	V07.xx
vizimax	Vizimax	PMU 010000	RMEN35000	21997-1 v1.1.4.2

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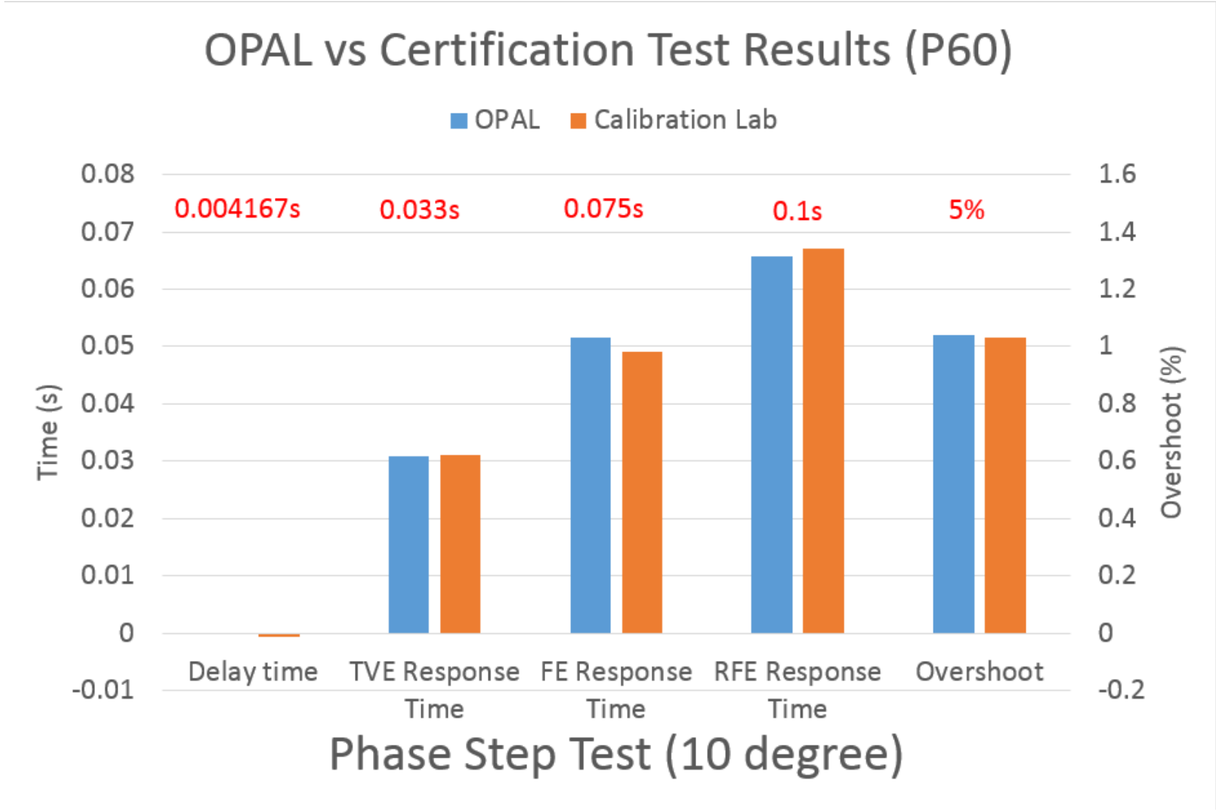
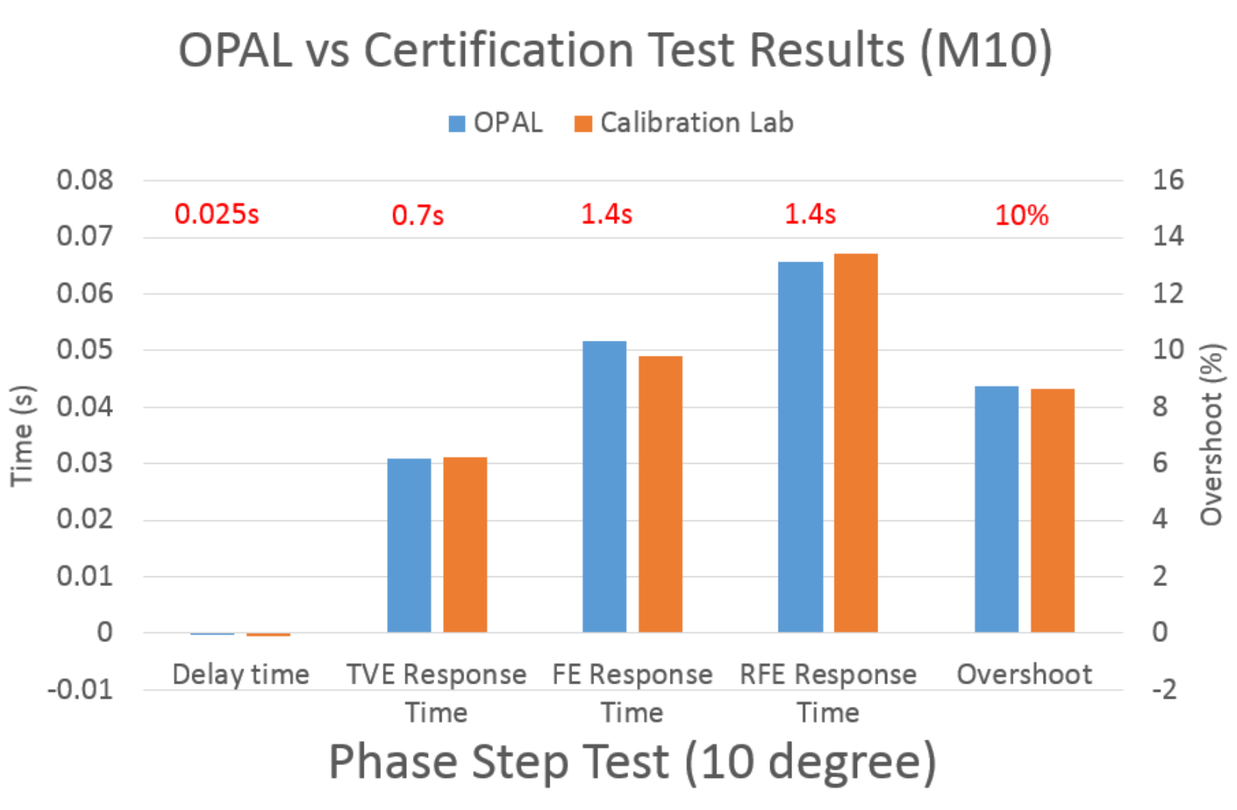
認証結果との比較　– ステップ変更テスト





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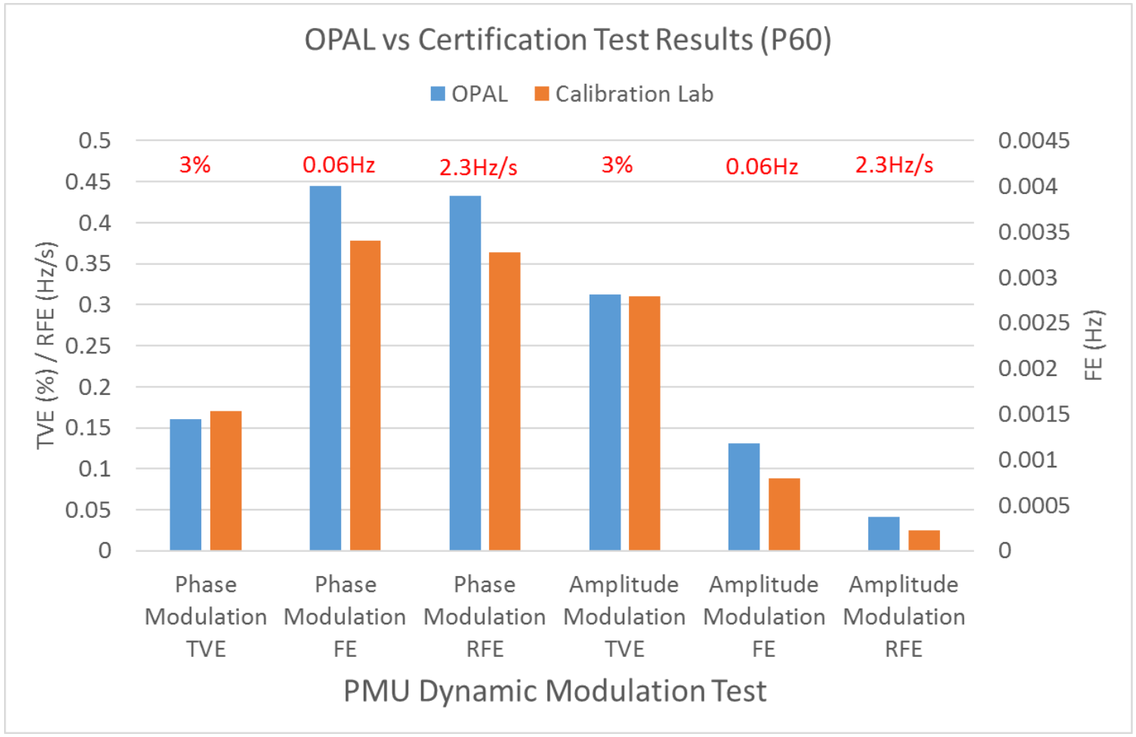
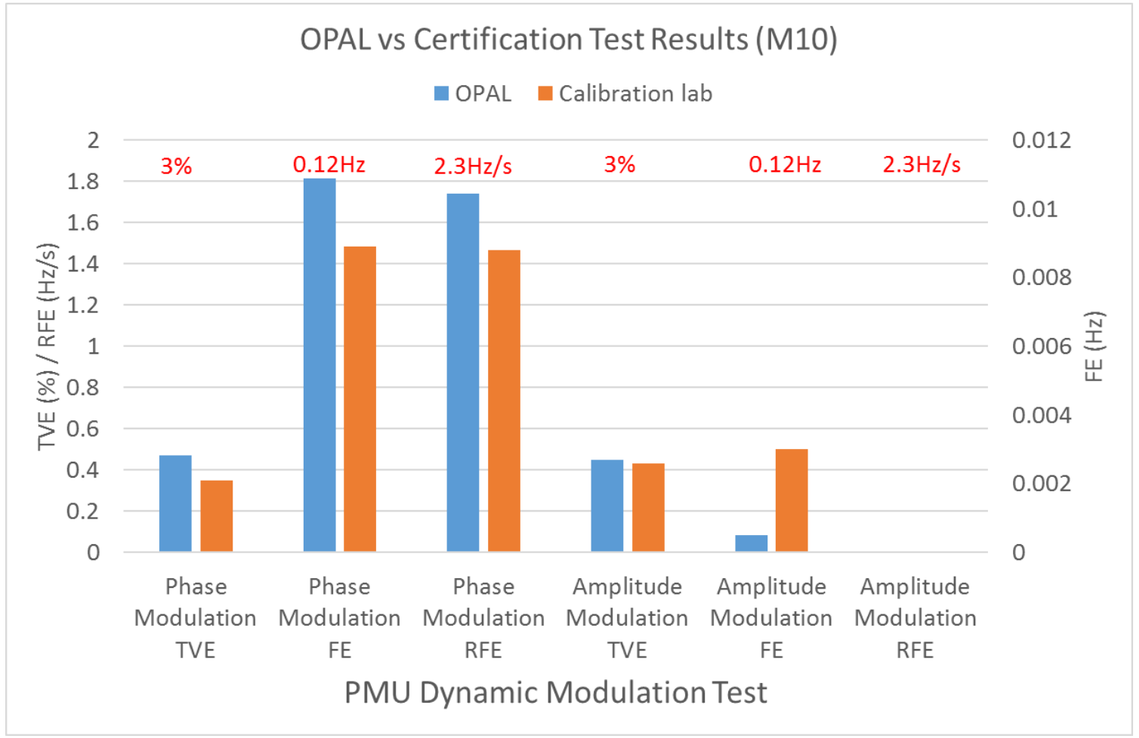
認証結果との比較　動的変調テスト





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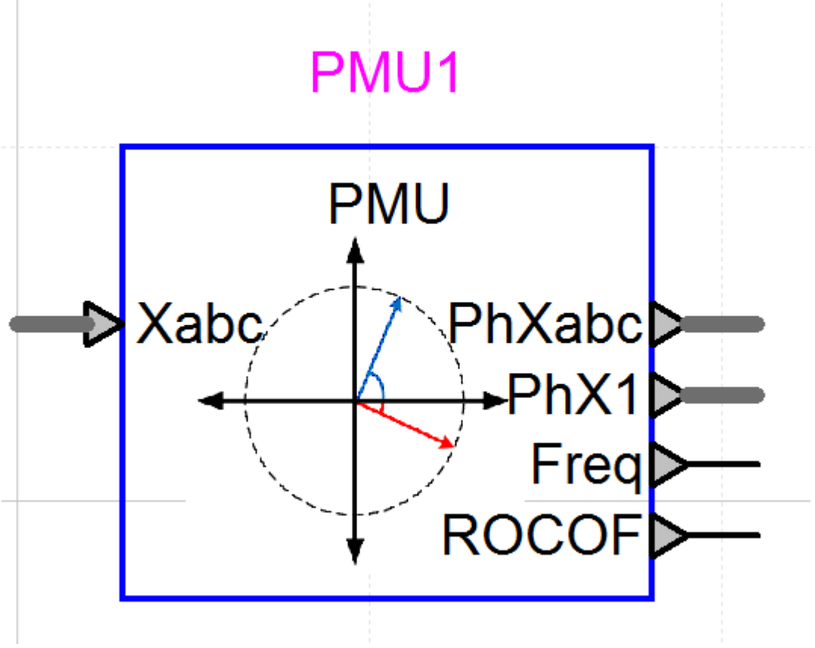
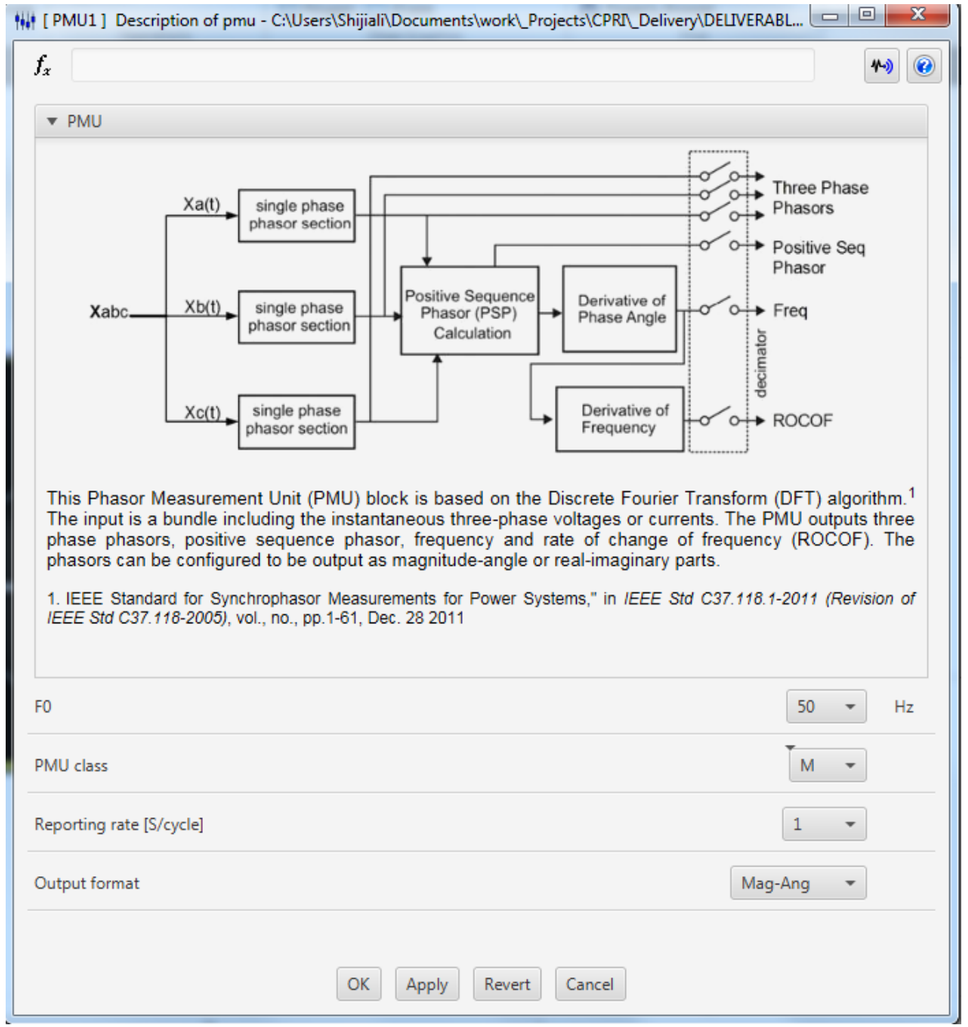
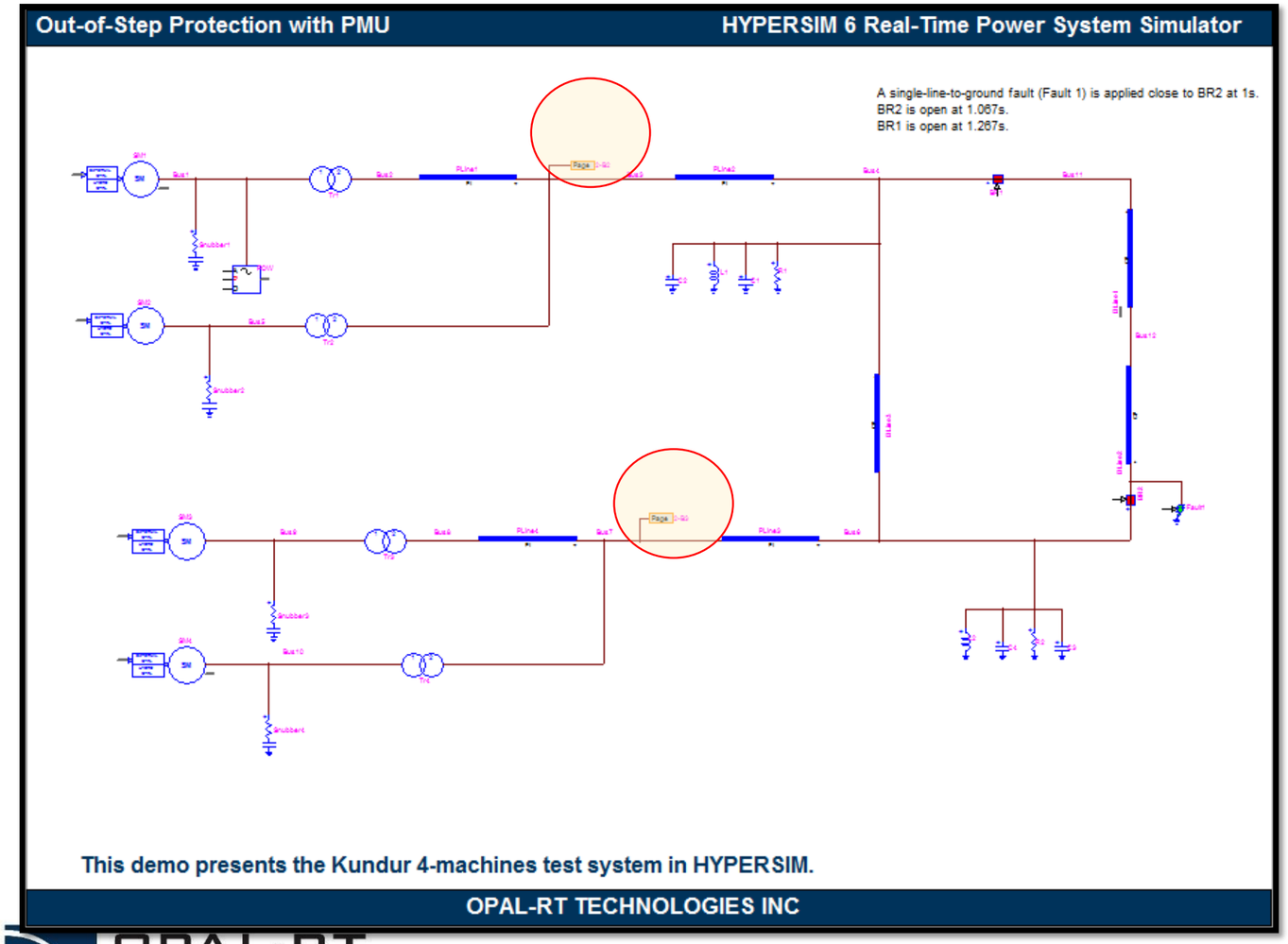
HYPERSIMで使われるモデル

- IEEE C37.118.1 – 2011　準拠





脱調検出の事例


Out-of-Step Protection with PMU
HYPERSIM 6 Real-Time Power System Simulator
A single-line-to-ground fault (Fault 1) is applied close to BR2 at 1s.
BR2 is open at 1.067s.
BR1 is open at 1.267s.
This demo presents the Kundur 4-machines test system in HYPERSIM.
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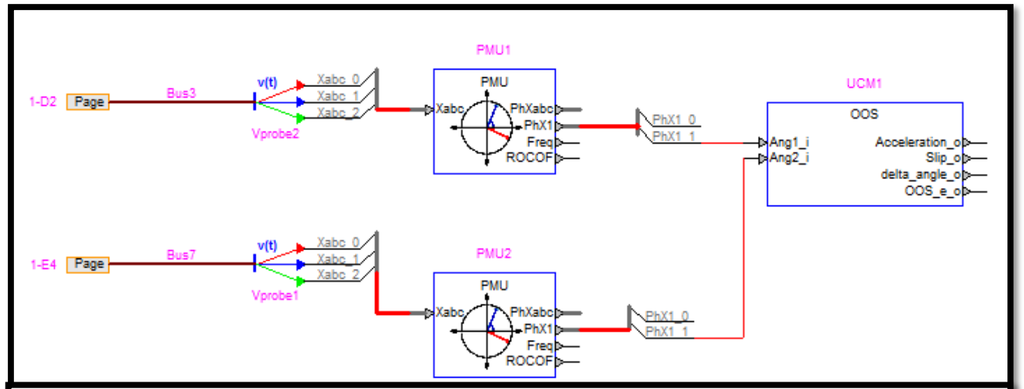
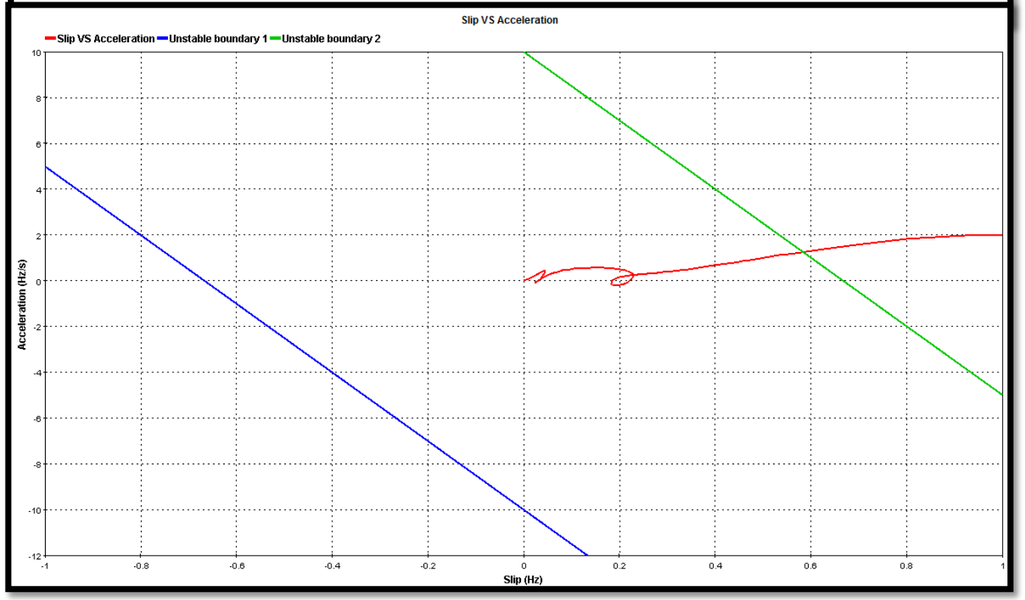

PMU1
1-D2
Page
Bus3
v(t)
Xabc_0
Xabc_1
Xabc_2
Vprobe2
PMU
Xabc
PhXabc
PhX1
Freq
ROCOF
PhX1_0
PhX1_1
UCM1
OOS
Ang1_i
Ang2_i
Acceleration_o
Slip_o
delta_angle_o
OOS_e_o
1-E4
Page
Bus7
v(t)
Xabc_0
Xabc_1
Xabc_2
Vprobe1
PMU2
PMU
Xabc
PhXabc
PhX1
Freq
ROCOF
PhX1_0
PhX1_1


Slip VS Acceleration
Slip VS Acceleration
Unstable boundary 1
Unstable boundary 2
Acceleration (Hz/s)
Slip (Hz)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1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