RTDS supported Hardware-in-the-loop PMU performance and compliance testing and PMU based applications

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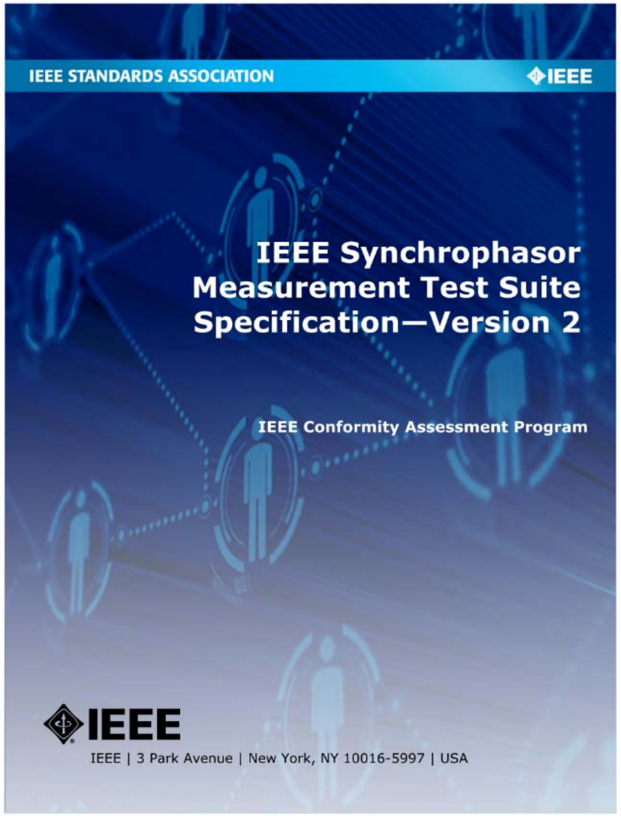
Part 1: RTDS supported Hardware-in-the-loop PMU performance and compliance testing

IEEE Synchrophasor Measurement Test Suite Specification—Version 2 (TSS)

RTDS supported Phasor Measurement Unit (PMU) evaluation platform is based on the TSS specification, which provides unambiguous test plans and requirements for equipment used during compliance testing.

Test procedures are within the normative of:

- IEEE Std. C37.118.1-2011
- IEEE Std. C37.118.1a-2014



IEEE STANDARDS ASSOCIATION
IEEE

IEEE Synchrophasor Measurement Test Suite Specification—Version 2

IEEE Conformity Assessment Program

IEEE
IEEE | 3 Park Avenue | New York, NY 10016-5997 | USA

Phasor Measurement Unit Performance and Complience Evaluation

Test suite specified procedures:

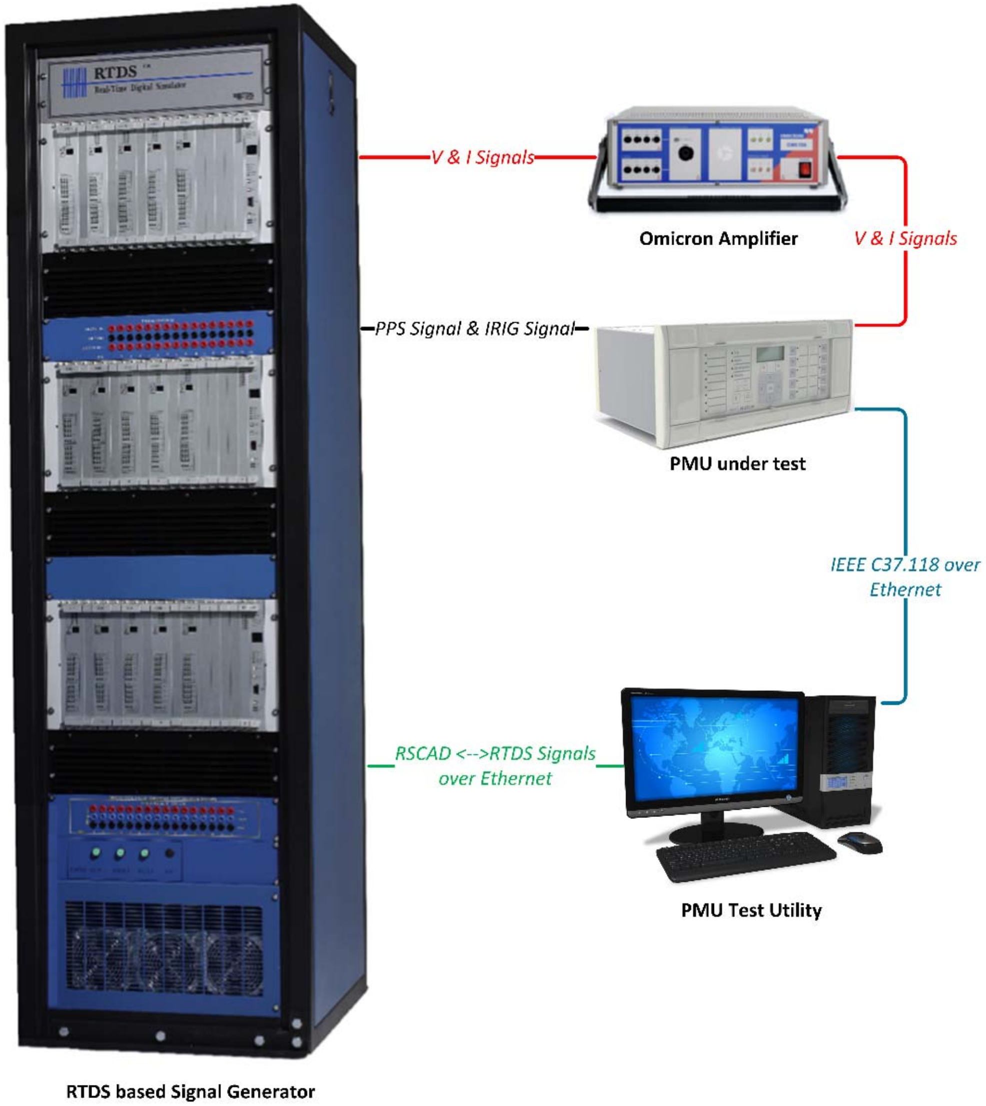
- Signal frequency range
  - *58 - 62 Hz, 0.1 Hz positive step*
  - *62 - 58 Hz, 0.1 Hz negative step*
- Signal magnitude
  - *Voltage: 0.8 -1.2 pu, 0.1 pu step*
  - *Current: 0.1-2 pu, 0.1 pu step*
- Phase angle
  - $f_{in} - f_o < 0.25$ *Hz, 0.05 Hz step*
- Harmonic distortion
  - *1% nominal magnitude, 2 - 50 harmonic, step 1 harmonic*

Phasor Measurement Unit Performance and Complience Evaluation

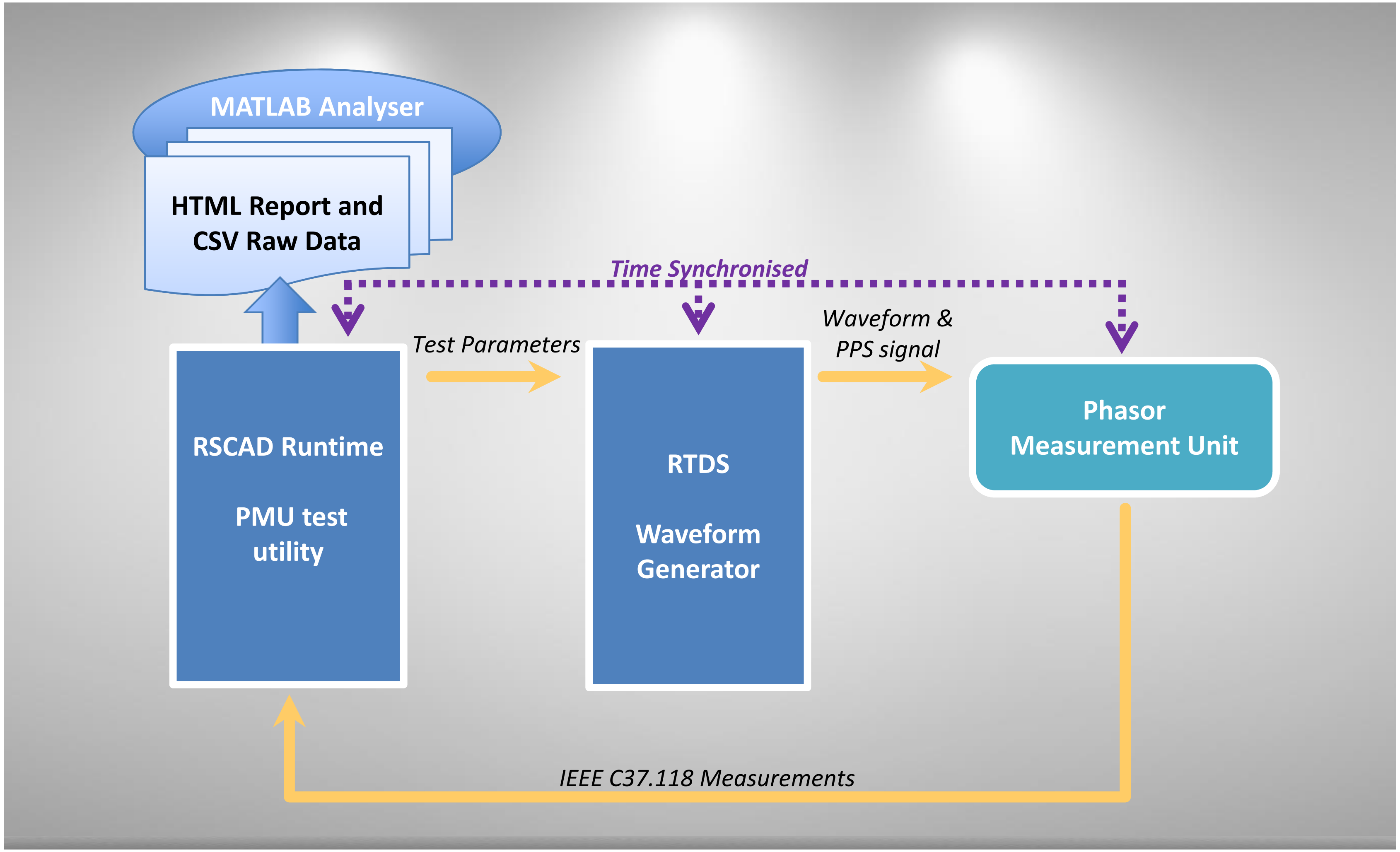
- Out-of-band interfering signals
  - *Required for M-class only*
- Measurement bandwidth
  - *Amplitude: 0.1 - 2 Hz, step 0.1 Hz*
  - *Phase: 0.1 - 2 Hz, step 0.1 Hz*
- Ramp of system frequency
  - *Positive* f_o *+ 2 Hz ramp, 1 Hz/s step*
  - *Negative* f_o *+ 2 Hz ramp, 1 Hz/s step*
- Step changes in phase and magnitude
  - *Amplitude: 1 ± 0.1 pu step*
  - *Angle: ± 10º step*
- PMU reporting latency compliance

RTDS Based Hardware-in-the-Loop Platform

- RTDS real-time digital simulator
  - GTWIF & PB5/GPC cards
  - GTAO D/A converter
  - Time sync provided by GTSYNC card
- Omicron amplifier
  - Generates V & I waveforms
- Alstom PMU under test
- RSCAD PMU Test Utility
  - Controls test parameters
  - Gathers PMU Data
  - Analyses data and exports results
- MATLAB Analyser
  - Performs data batch analysation



RTDS based PMU Performance Evaluation Platform Diagram



MATLAB Analyser

HTML Report and CSV Raw Data

Time Synchronised

Test Parameters

Waveform & PPS signal

RSCAD Runtime

PMU test utility

RTDS

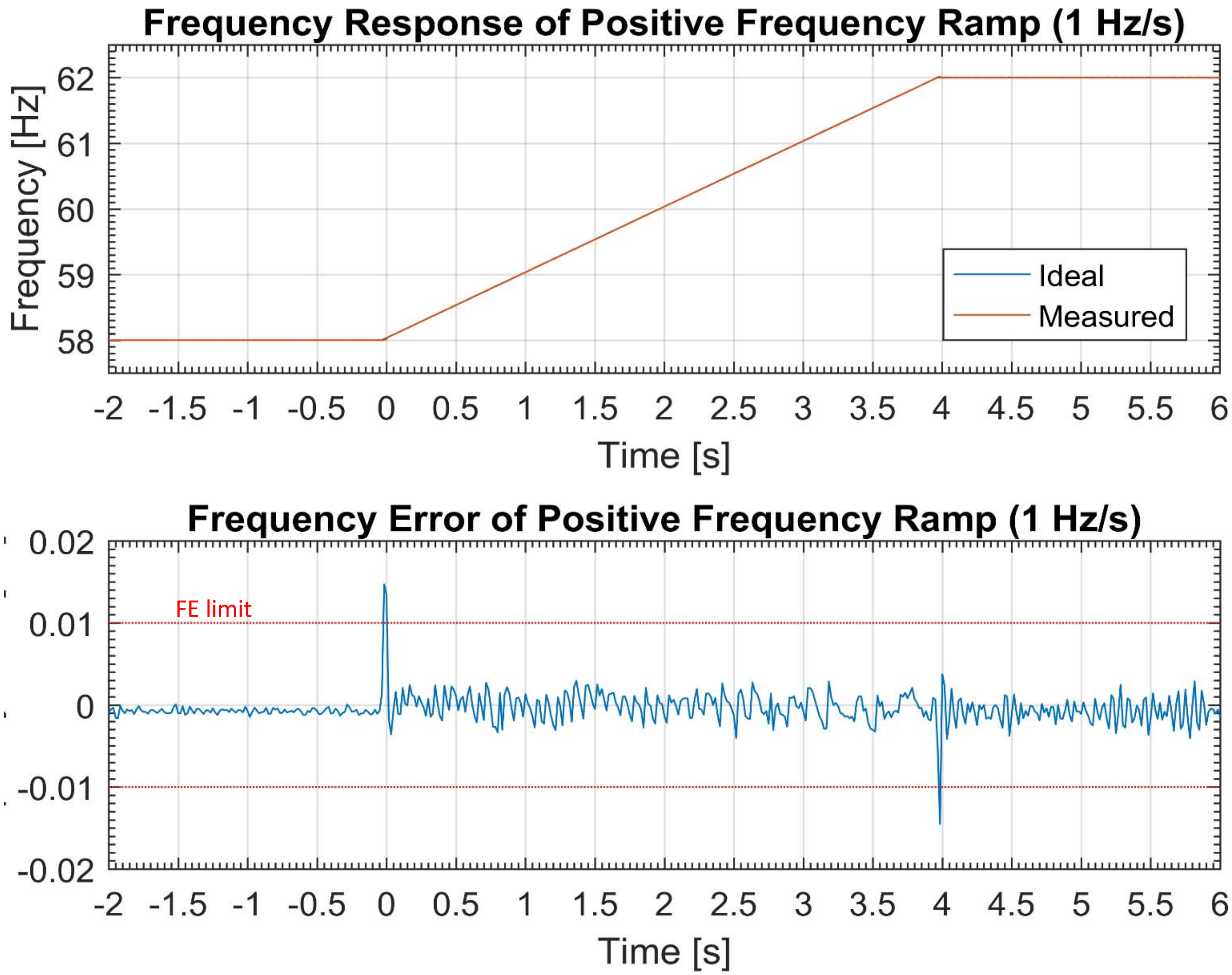
Waveform Generator

Phasor Measurement Unit

IEEE C37.118 Measurements

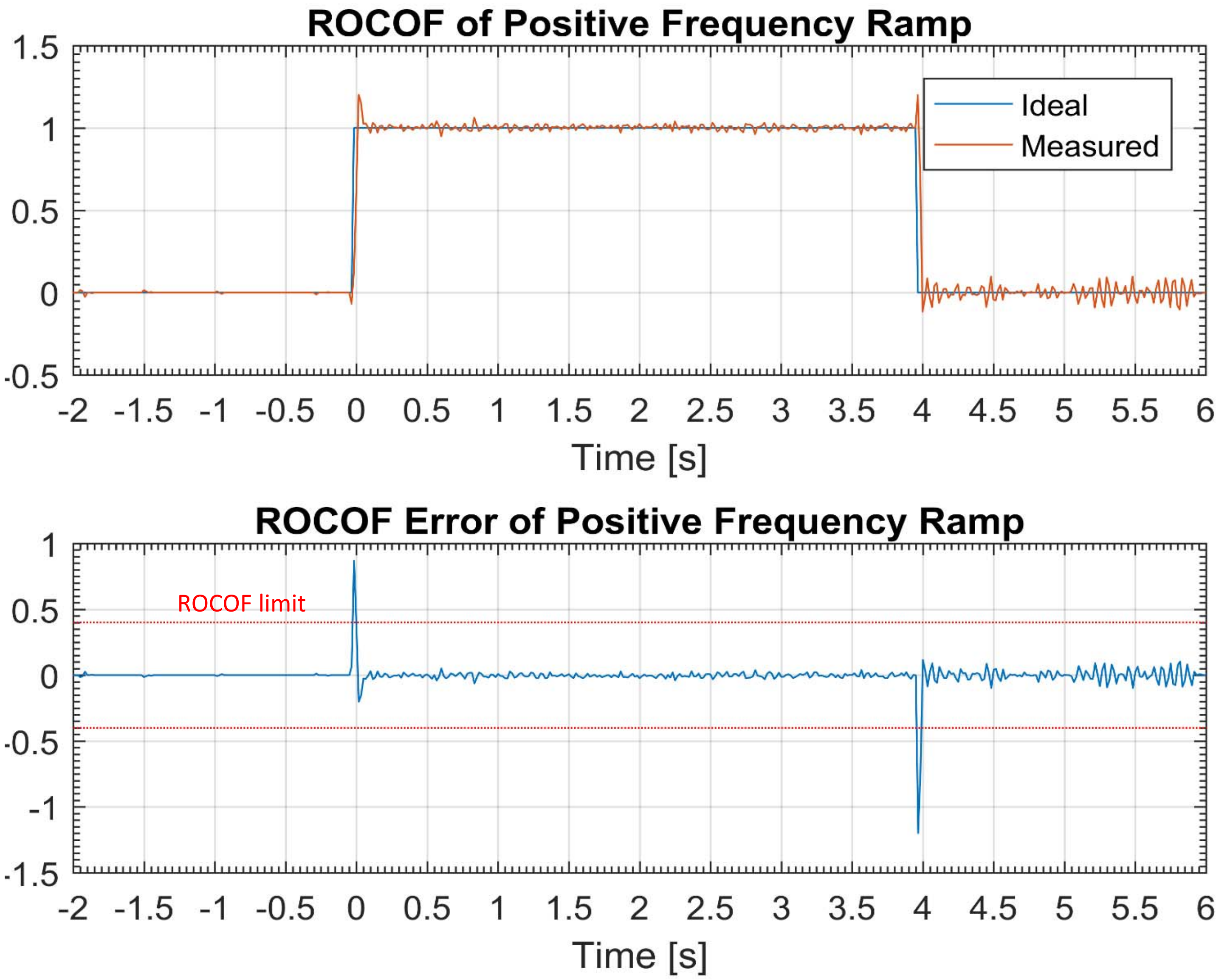
Positive Frequency Ramp Response

P-class PMU



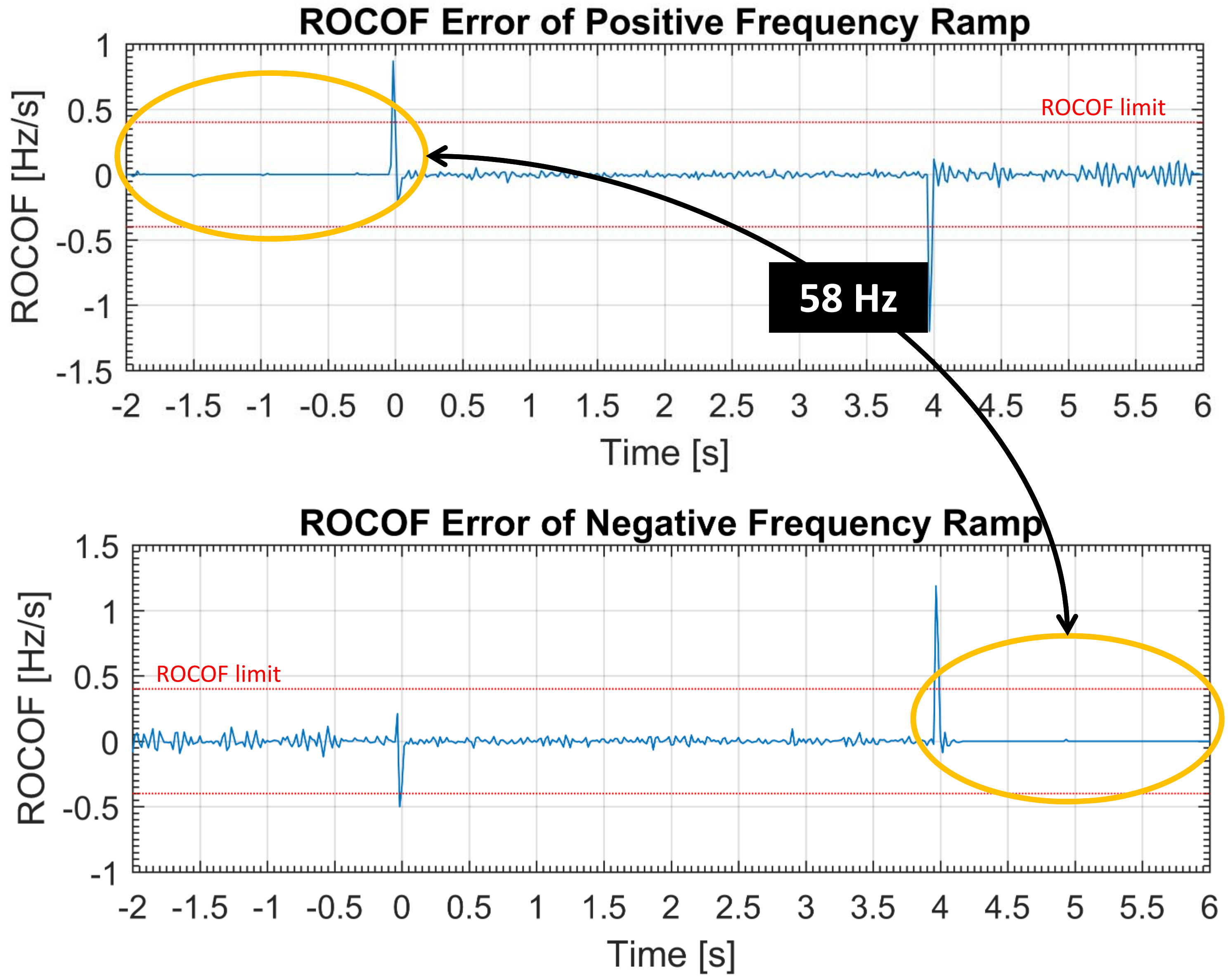
Positive Frequency Ramp Response

P-class PMU



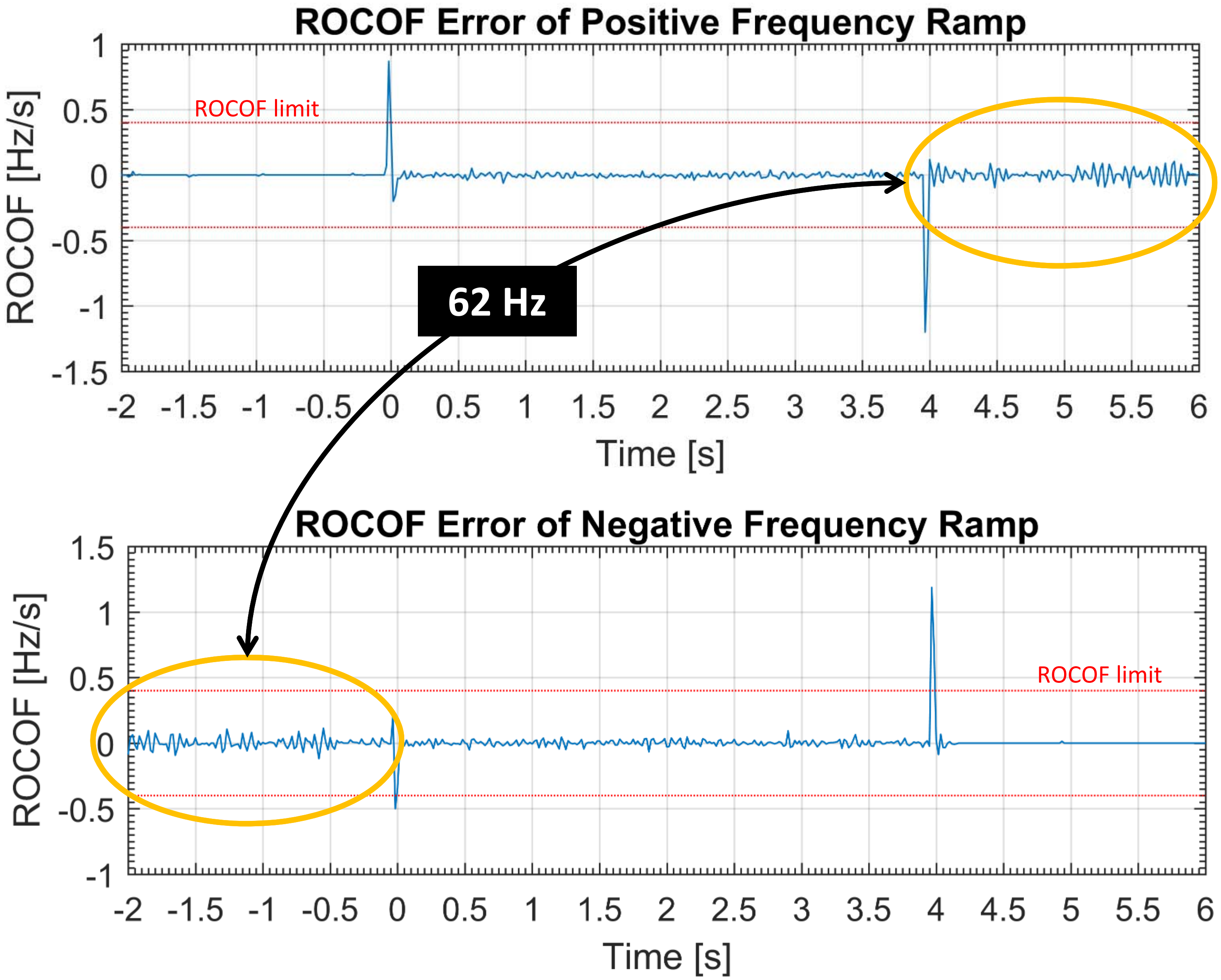
Positive Frequency Ramp Response

P-class PMU



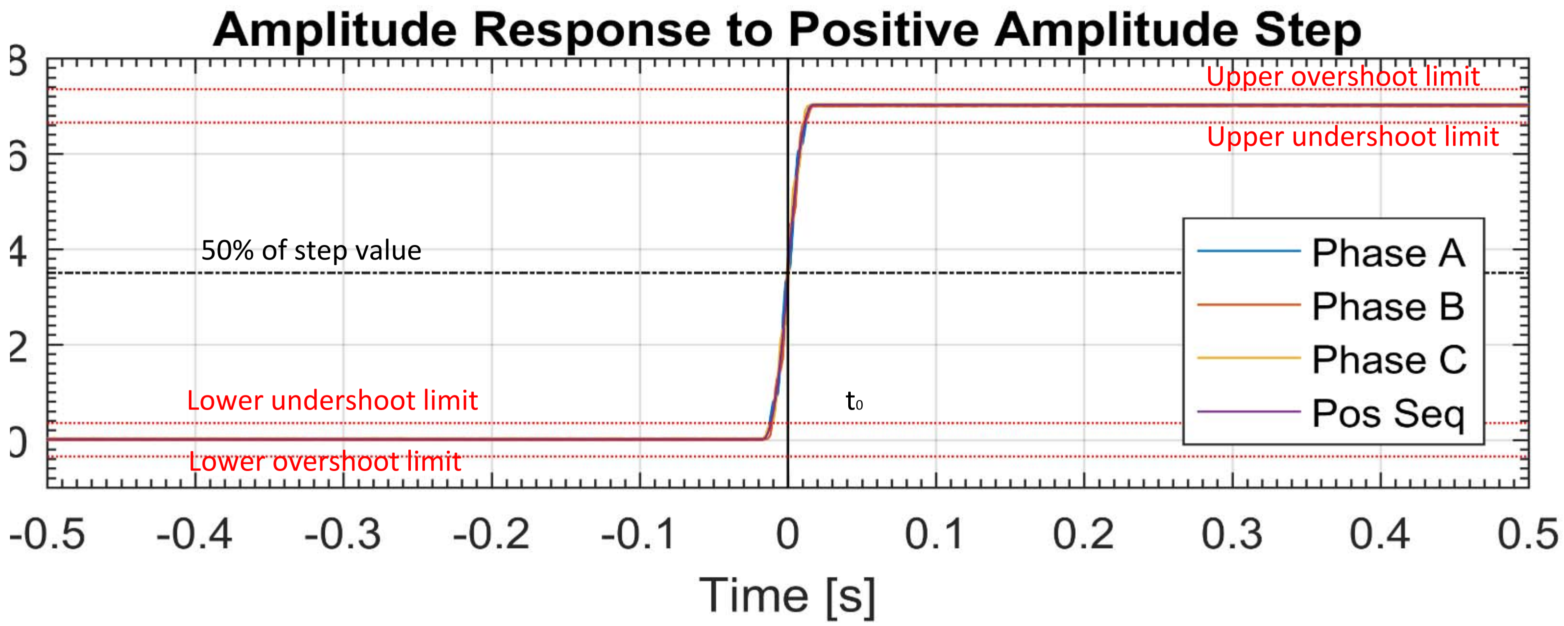
Positive Frequency Ramp Response

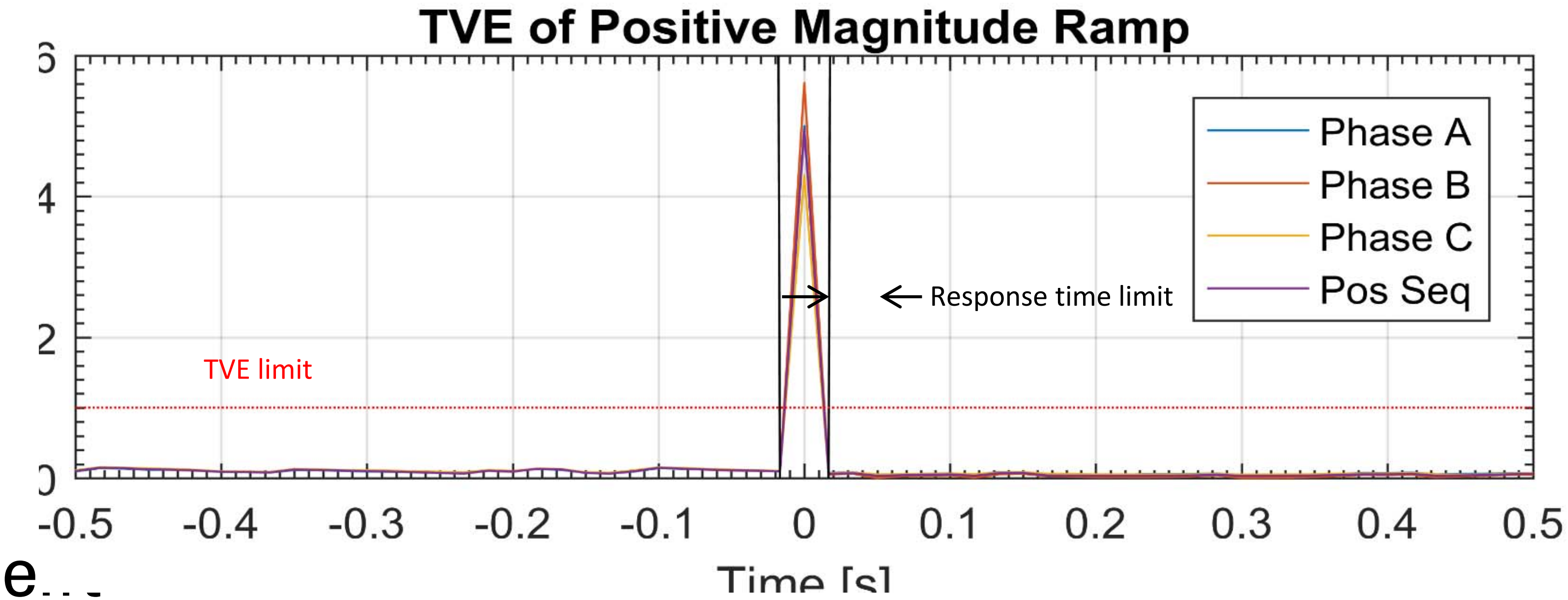
P-class PMU



Positive Amplitude Step Response

P-class PMU


Amplitude Response to Positive Amplitude Step

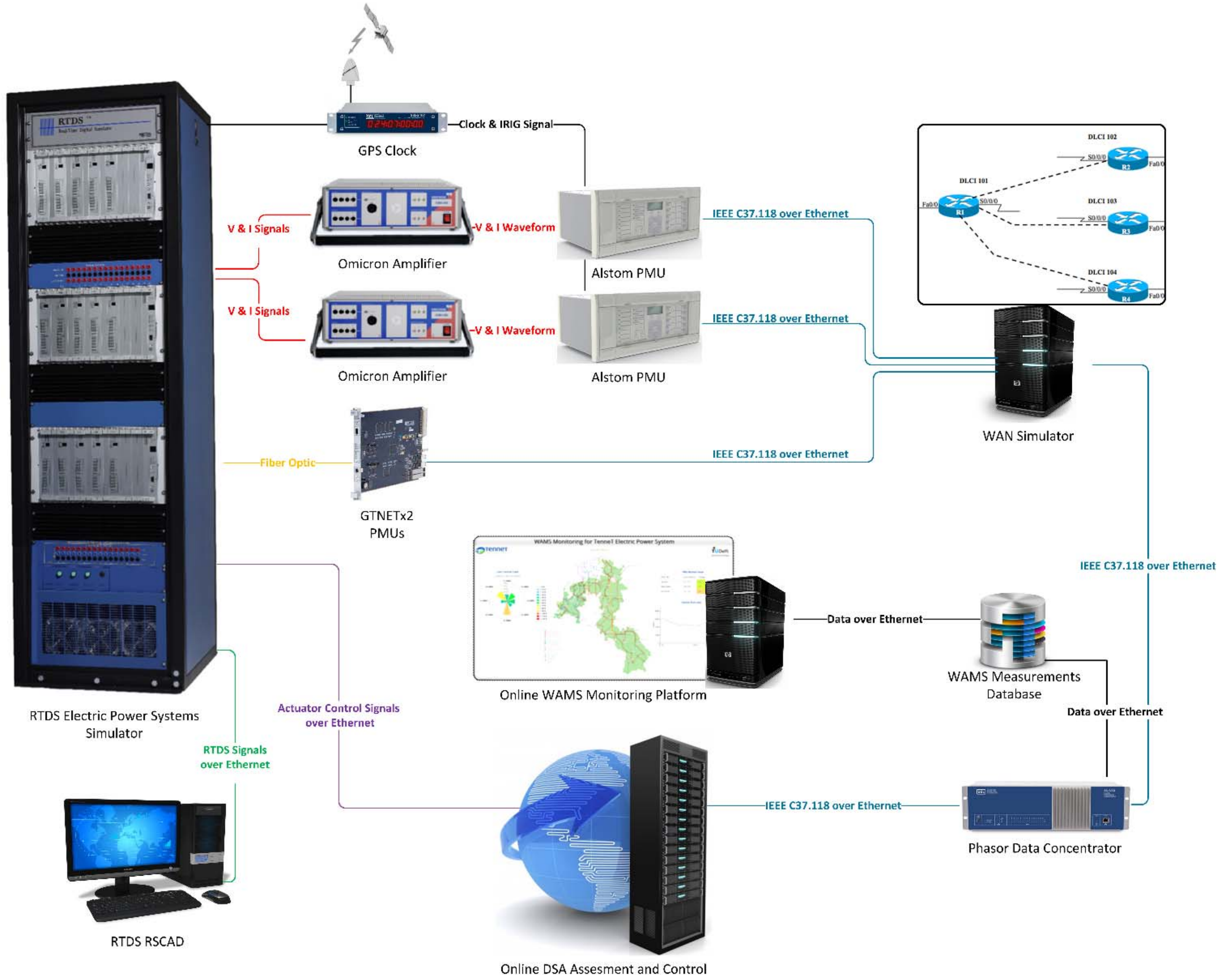

TVE of Positive Magnitude Ramp

PMU Evaluation Results

Test		**Pass/ Fail Test**		
Test type	Test subtype	**Frequency**	**ROCOF**	**TVE**
Steady state	Signal Frequency Range	✓	✓	✓
Steady state	Signal Magnitude—Voltage	✓	✓	✓
Steady state	Signal Magnitude—Current	✓	✓	✓
Steady state	Phase Angle Deviation	✓	✓	✓
Steady state	Harmonic Distortion	✓	✓	✓
Steady state	Out-of-Band Interference	(Required for M class only)		
Dynamic	Measurement Bandwidth—phase modulation	✓	✓	✓
Dynamic	Measurement Bandwidth—amplitude modulation	✓	✓	✓
Dynamic	Ramp of System Frequency	✗	✗	✗
Dynamic	Step Change in Phase	✗	✓	✗
		Delay: ✓	Response: ✗	Overshoot: ✓
Dynamic	Step Change in Magnitude	✗	✓	✗
		Delay: ✓	Response: ✓	Overshoot: ✓
Latency	PMU Reporting Latency	(Not performed)		

Part 2: Phasor Measurement Unit data driven Applications

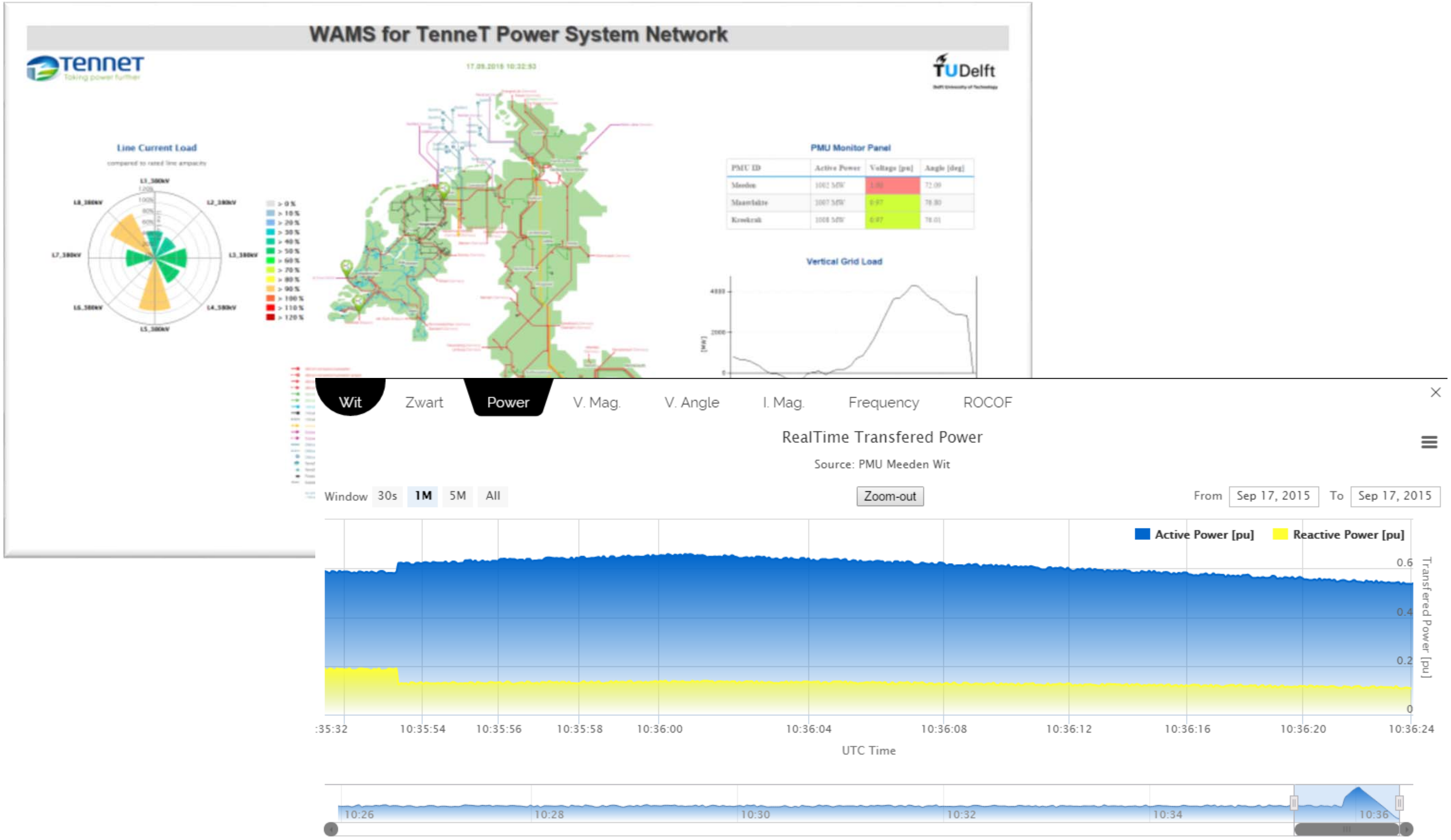
WAMS supported Real-Time based Electric Power System test bed with Hardware and Software in the loop



WAMS supported RTDS based EPS test bed

Real-time Wide Area Monitoring Platform

Web based WAMS platform



WAMS for TenneT Power System Network

PMU Monitor Panel

PMU ID	Active Power	Voltage [pu]	Angle [deg]
Meeden	1002 MW	1.00	72.09
Maasvlakte	1007 MW	0.97	78.80
Kreekrak	1008 MW	0.97	78.01

RealTime Transfered Power

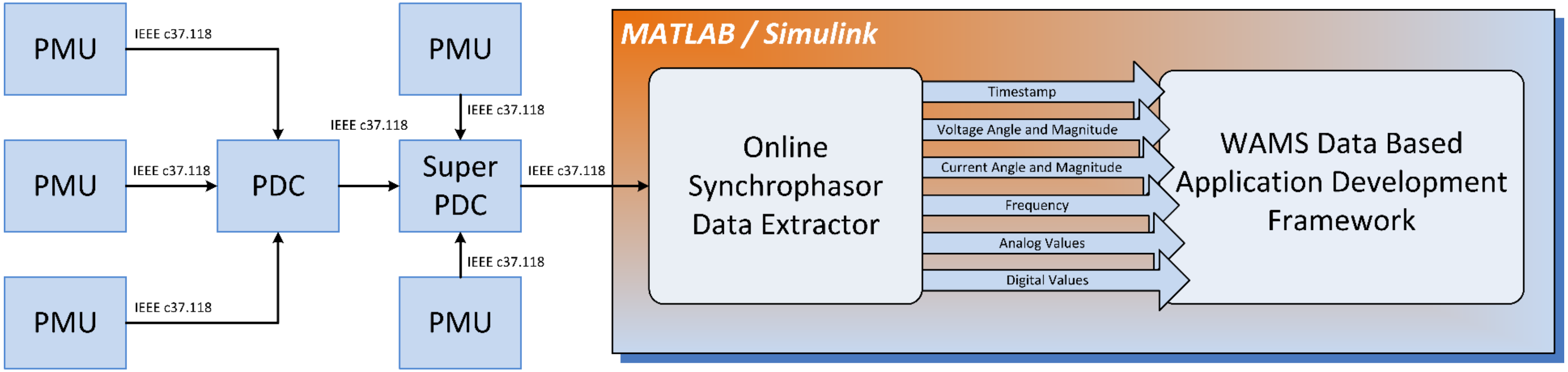
Source: PMU Meeden Wit

From Sep 17, 2015 To Sep 17, 2015

MATLAB Supported WAMS Data Based Application Development Framework

Main features:

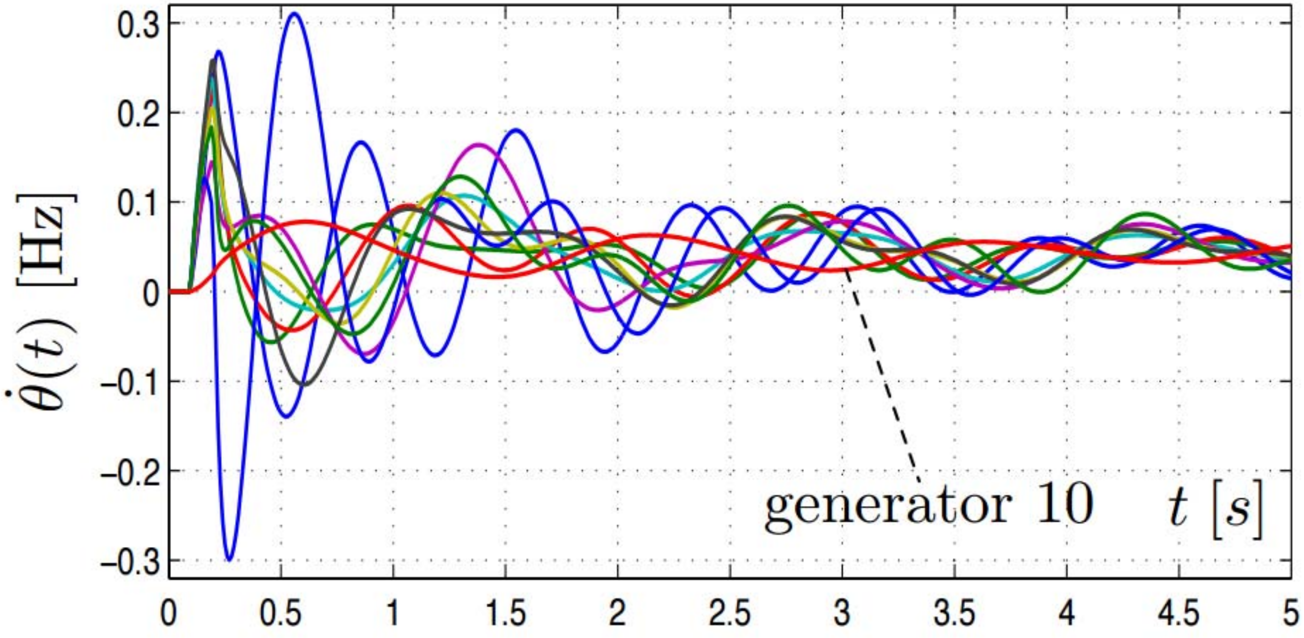
- Connects to the PMU/PDC synchrophasor stream via the **IEEE C37.118.2** protocol.
- Supports **2 way communication** over TCP and UDP protocols.
- Automatically reads PMU Configuration frame info (scaling factors, station and channel names, reporting rate, time quality status flags etc).
- Received measurements are available in MATLAB Workspace in real-time.



PMU Measurement supported Online Slow and Fast Generator Coherency Identification

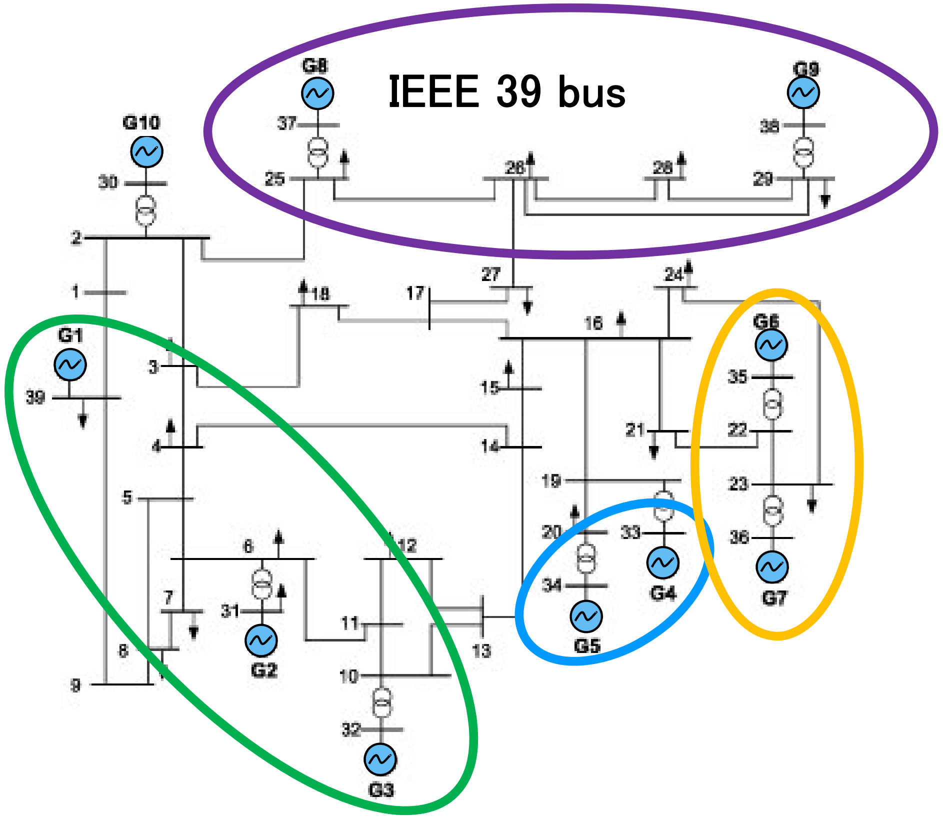
Intro:

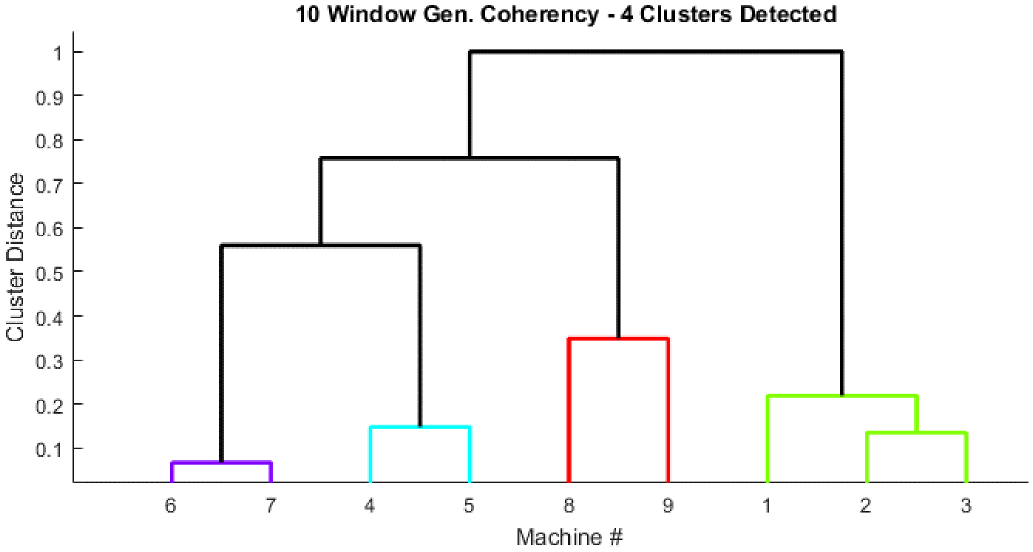
- Generator coherency identification is based on mutual electromechanical oscillations.



Example: PMU supported Generator Coherency Identification and Clustering on IEEE 39 bus

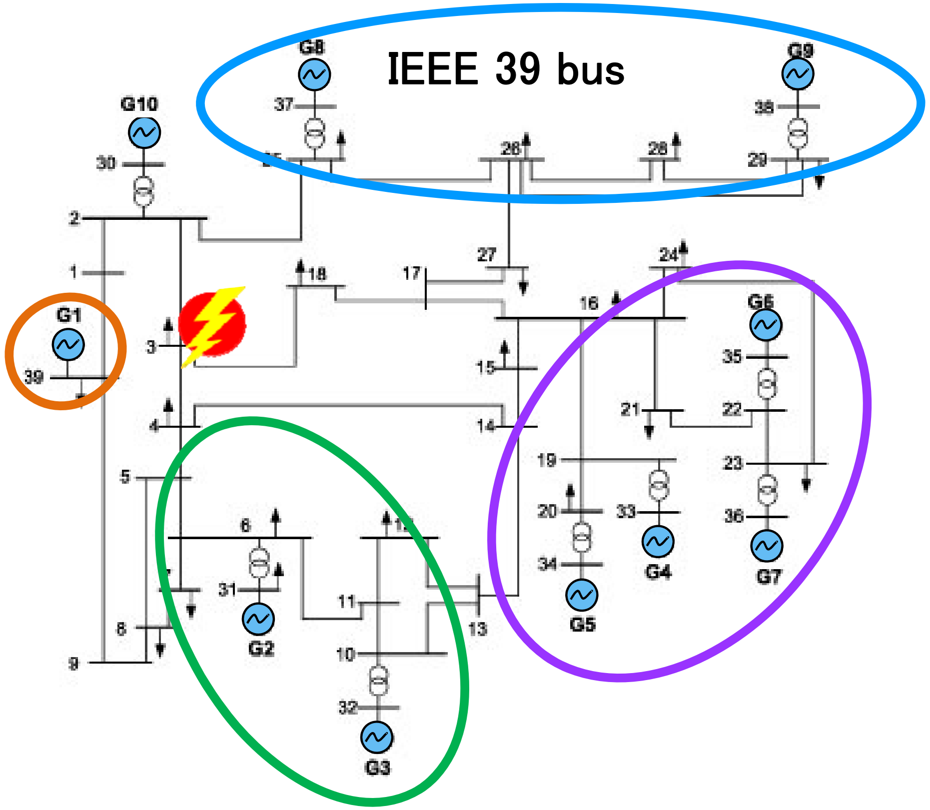
1. Slow Generator Coherency during semi-stationary conditions





Example: PMU supported Generator Coherency Identification and Clustering on IEEE 39 bus

2. Fast Generator Coherency after fault on line between Bus 3 and Bus 4



Conclussion

- IEEE Synchrophasor Measurement Test Suite Specification—Version 2 provides solid framework for PMU performance evaluation platforms.
- Better PMU estimation algorithm required under dynamic conditions.
- RTDS based PMU performance evaluation platform uncertainty is under investigation.
- MATLAB Supported WAMS Data Based Application Development Framework serves as a valuable tool fot fast prototyping and testing of online synchrophasor based applications.
- With using WAMS supported real-time electric power system testbed the performance of each component can be evaluated and exanimated towards overall performance of the proposed WAMS based solution.

Publications

- P. Ceferin, M. Naglic, A. Souvent, Wide Area Monitoring Systems and Information and Communication Technology Networks, accepted for CIGRE Science & Engineering Journal, June 2016

- M. Naglic, I. Tyuryukanov, M. Popov, M. V. D. Meijden, V. Terzija: Phasor Measurement Unit supported Online Generator Slow-Coherency Identification, under review for MedPower 2016

- I. Tyuryukanov, J. Quiros-Tortos, M. Naglic, M. Popov, M. V. D. Meijden, V. Terzija, Controlled Islanding of Power Networks based on Graph Reduction and Spectral Clustering, under review for MedPower 2016

- M. Popov, M. Naglic, I.Tyuryukanov, G. Rietveld, M. van der Meijden, A contribution to Synchrophasor Testing and HIL testing of PMUs for system disturbance monitoring, accepted for IEEE PES GM Panel Session 2016

Experience with testing of negative sequence relays for the protection against internal motor faults

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Master Thesis of
Aravinth T.S.

Scenario

- A turn-turn fault occurred in one phase of an Induction Motor's stator
- Asymmetrical voltage causing bearing damage (pitting) , little reduction in RPM (vibratory)
- Fault was not detected by the relay resulting in a development of the turn-turn fault into Phase-Phase fault after 9 minutes
- Tripping of the system after 9 minutes at extremely high current
- Final scenario: Stator Core damage, Rotor and accessories due to excessive heating (Unplanned shutdown and production loss)

PROBLEM STATEMENT

Failure of Protection system to detect the turn-turn fault at the inception stage

RESEARCH QUESTION

- The reason behind the failure of imminent fault detection
- Setting of the motor protection relay, if employed

APPROACH

1. Literature review on Internal faults in Induction motors and Protective relaying
2. Formulation of algebraic equations for modeling Turn-Turn fault
3. Simulation of Turn-Turn fault in EMTP-ATP MODELS (Dynamic State)
4. Obtain COMTRADE file (.PL4 / .CFG)
5. Feed COMTRADE file into Omicron for Secondary Current Injection
6. Testing of Siprotec-4 protection relay (7SJ645) for Negative sequence & Over current protection for various levels of fault severity in stator
7. Propose Optimised Protection settings

Simulation

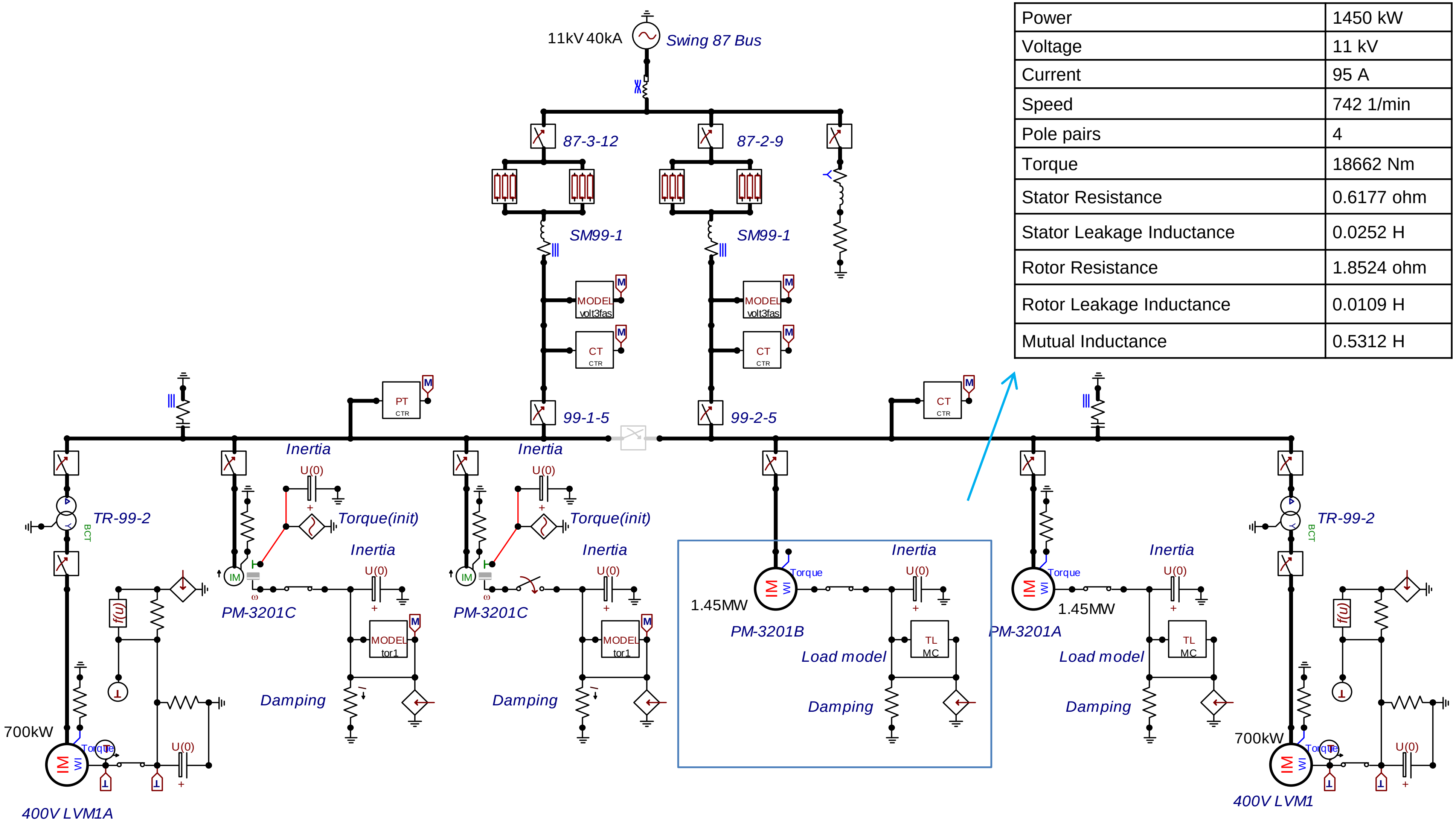
Testing

Optimization

<u>COMTRADE</u>: Common Format for Transient Data Exchange for Power Systems

SIMULATION

DOW NETWORK MODEL



Power	1450 kW
Voltage	11 kV
Current	95 A
Speed	742 1/min
Pole pairs	4
Torque	18662 Nm
Stator Resistance	0.6177 ohm
Stator Leakage Inductance	0.0252 H
Rotor Resistance	1.8524 ohm
Rotor Leakage Inductance	0.0109 H
Mutual Inductance	0.5312 H

Source: *DOW Benelux, Terneuzen*

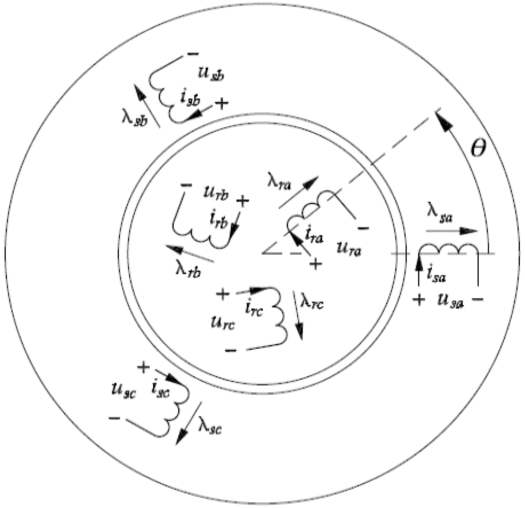
MATHEMATICAL MODELLING OF INDUCTION MACHINE

1. Assumptions

- Stator and rotor windings are sinusoidally distributed in space & replaced by an equivalent concentrated winding
- Equal number of stator turns in all phases
- Infinitely permeable iron
- Saliency effects, the slotting effects are neglected
- Space harmonics of the stator and rotor magnetic flux are negligible
- Magnetic saturation, core loss and skin effect are negligible
- Windings resistance and reactance do not vary with the temperature
- End and fringing effects are neglected

2. DQ0 Transformation (Park’s Transformation)

3. Choice of Reference Frame for Simulation



Parks' Transformation:

$$X_{dqo} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix}$$

Steady State Equations:

$$U_{qs} = R_s i_{qs} + \omega\lambda_{ds} + \frac{d\lambda_{qs}}{dt}$$

$$U_{ds} = R_s i_{ds} - \omega\lambda_{qs} + \frac{d\lambda_{ds}}{dt}$$

$$U_{0s} = R_s i_{0s} + \frac{d\lambda_{0s}}{dt}$$

$$U_{qr} = R_r i_{qr} + (\omega - \omega_r)\lambda_{dr} + \frac{d\lambda_{qr}}{dt}$$

$$U_{dr} = R_r i_{dr} - (\omega - \omega_r)\lambda_{qr} + \frac{d\lambda_{dr}}{dt}$$

$$U_{0r} = R_r i_{0r} + \frac{d\lambda_{0r}}{dt}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr}$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\lambda_{0s} = L_{ls} i_{0r}$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$

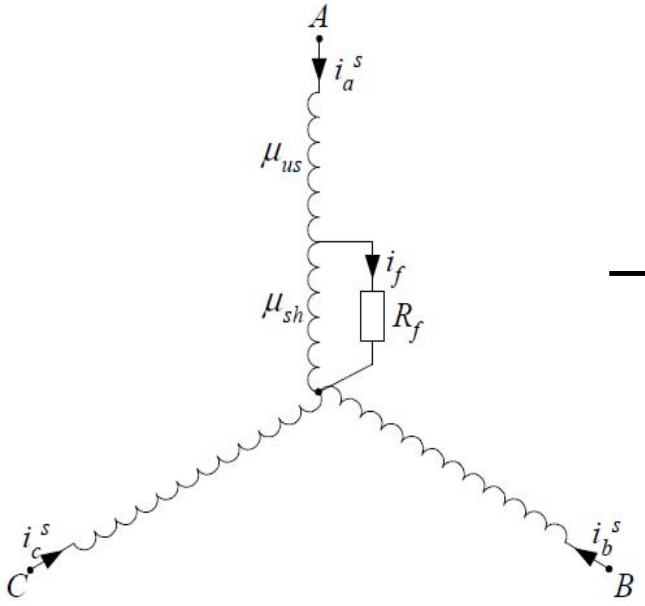
$$\lambda_{0r} = L_{lr} i_{0r}$$

$$T_{em} = \frac{P}{2}\frac{3}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr})$$

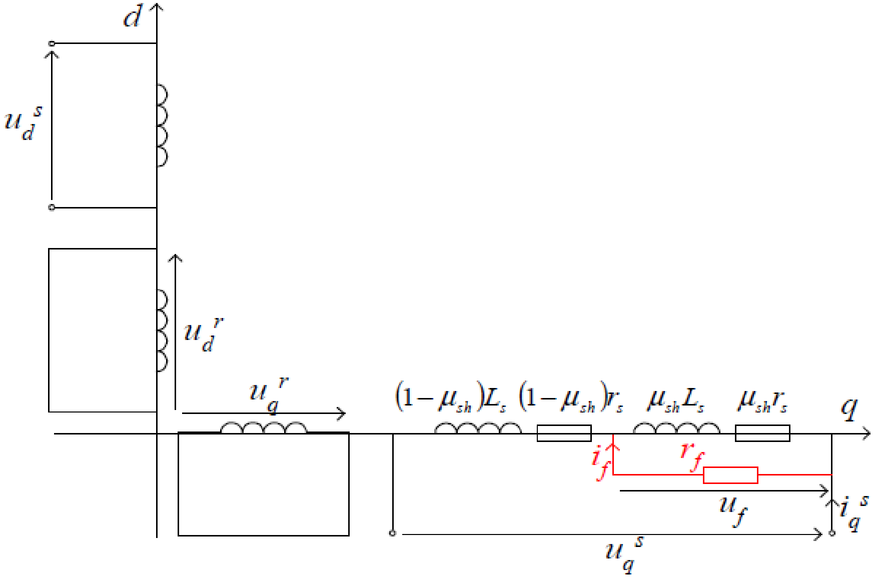
$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_{em} - T_L)$$

STATOR TURN-TURN FAULT

Representation in ‘abc’ frame



Representation in ‘dq0’ frame



Source: *M.Wieczorek and E.Rosolowski “Modelling of IM for Simulation of Internal Faults”, Wroclaw University of Technology*

EQUATIONS FOR TURN-TURN FAULT

‘abc’ frame

$$\frac{d\lambda_{abc}^{s}}{dt} = U_{abc}^{s} - R_s(i_{abc}^{s} - \mu_{abc} i_f)$$

$$\frac{d\lambda_{abc}^{r}}{dt} = -R_r i_{abc}^{r}$$

$$\frac{d\lambda_{a}^{sh}}{dt} = R_f i_f - R_s \mu_{sh}(i_a^s - i_f)$$

$$\lambda_{abc}^{s} = L_s(i_{abc}^{s} - \mu_{abc} i_f) + L_m i_{abc}^{r}$$

$$\lambda_{abc}^{r} = L_m(i_{abc}^{s} - \mu_{abc} i_f) + L_m i_{abc}^{r}$$

‘dq’ frame

$$\frac{d\lambda_{qs}}{dt} = U_{qs} - R_s(i_{qs} - \sqrt{\frac{2}{3}}\mu_{sh} i_f)$$

$$\frac{d\lambda_{ds}}{dt} = U_{ds} - R_s i_{ds}$$

$$\frac{d\lambda_{q}^{sh}}{dt} = R_f i_f - \mu_{sh} R_s(i_{qs} - i_f)$$

$$\frac{d\lambda_{qr}}{dt} = \omega_r \lambda_{dr} - R_r i_{qr}$$

$$\frac{d\lambda_{dr}}{dt} = -\omega_r \lambda_{qr} - R_r i_{dr}$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} - \sqrt{\frac{2}{3}}\mu_{sh} L_s i_f$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$

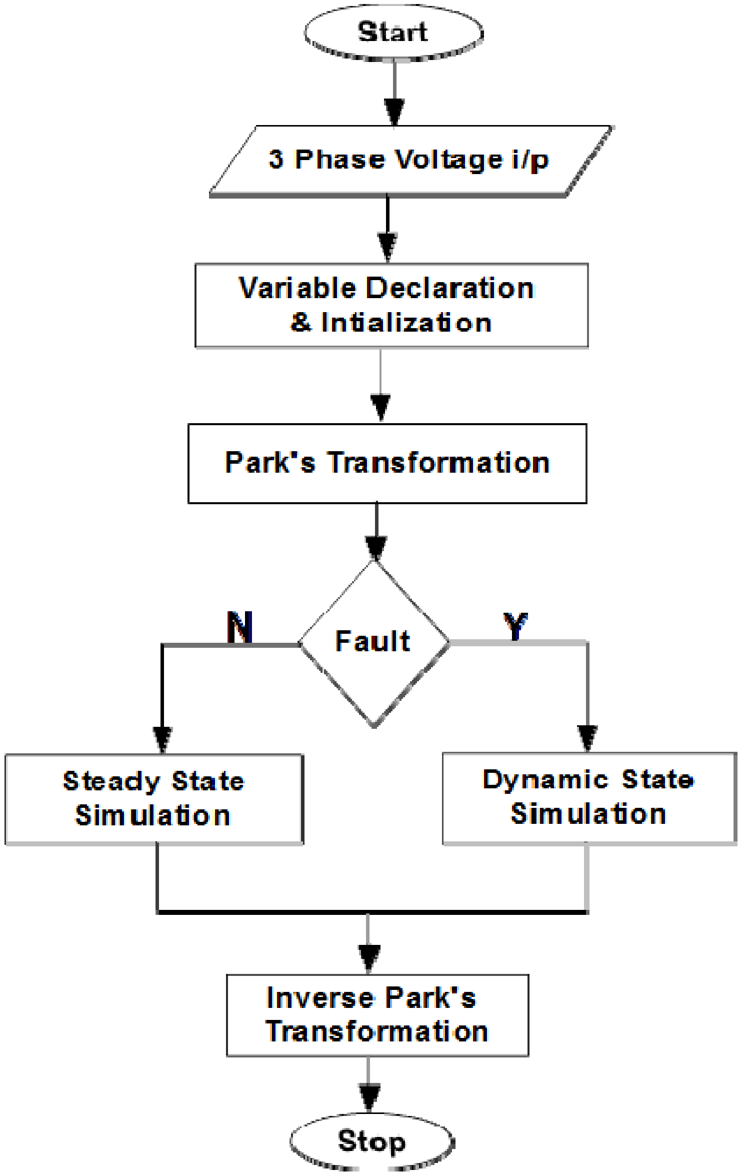
$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} - \sqrt{\frac{2}{3}}\mu_{sh} L_m i_f$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$

$$\lambda_{q}^{sh} = \mu_{sh} L_{ls}(i_{qs} - i_f) + \mu_{sh} L_m(i_{qs} + i_{qr} - \sqrt{\frac{2}{3}}\mu_{sh} i_f)$$

$$T_{em} = \frac{3}{2}\frac{P}{2} L_m(i_{qs} i_{dr} - i_{ds} i_{qr}) - \frac{P}{2} L_m \mu_{sh} i_f i_{qr}$$

SIMULATION IN MODELS IN EMTP

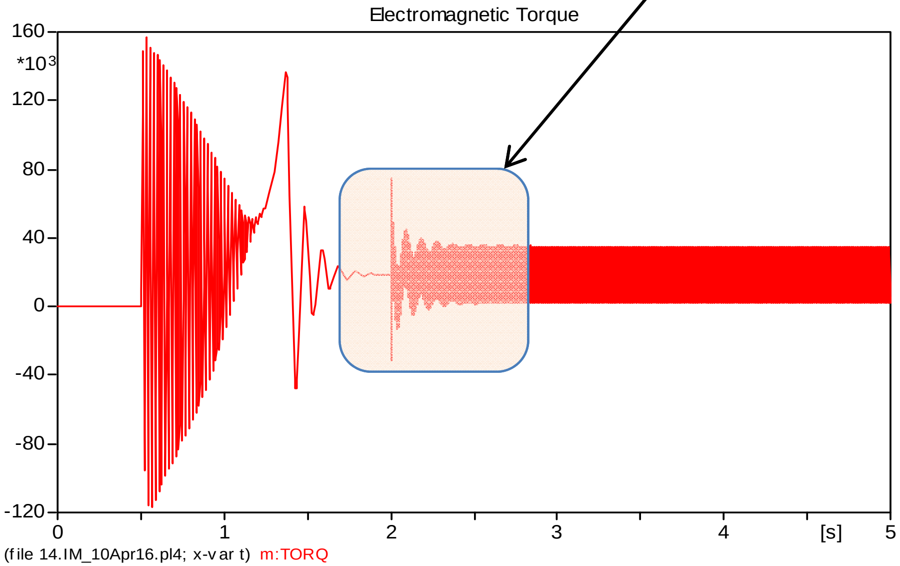


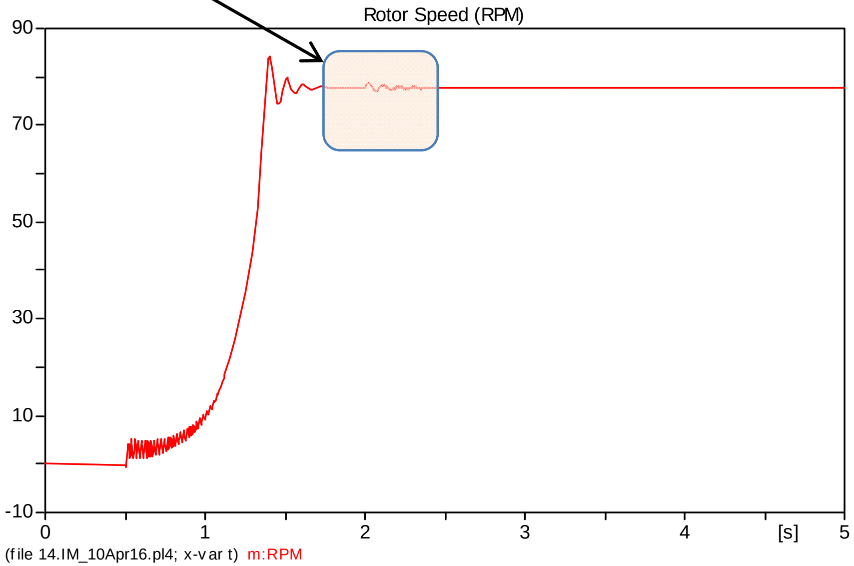
<u>Why MODELS?</u>

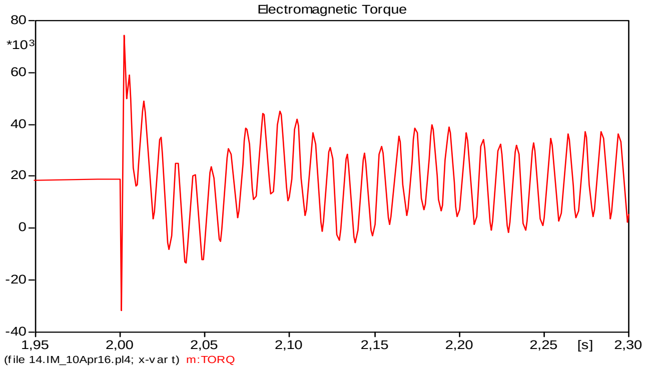
- General technical description language supported by simulation solver.
- Flexible for performing numerical and logical manipulation of variables in time domain
- Omicron reads pl4 files

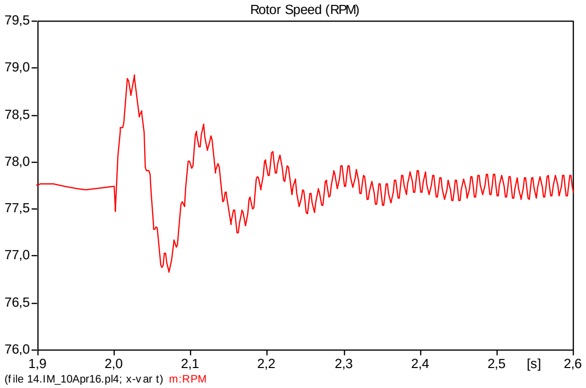
O/P - TORQUE & SPEED

Simulation of fault at 2 second

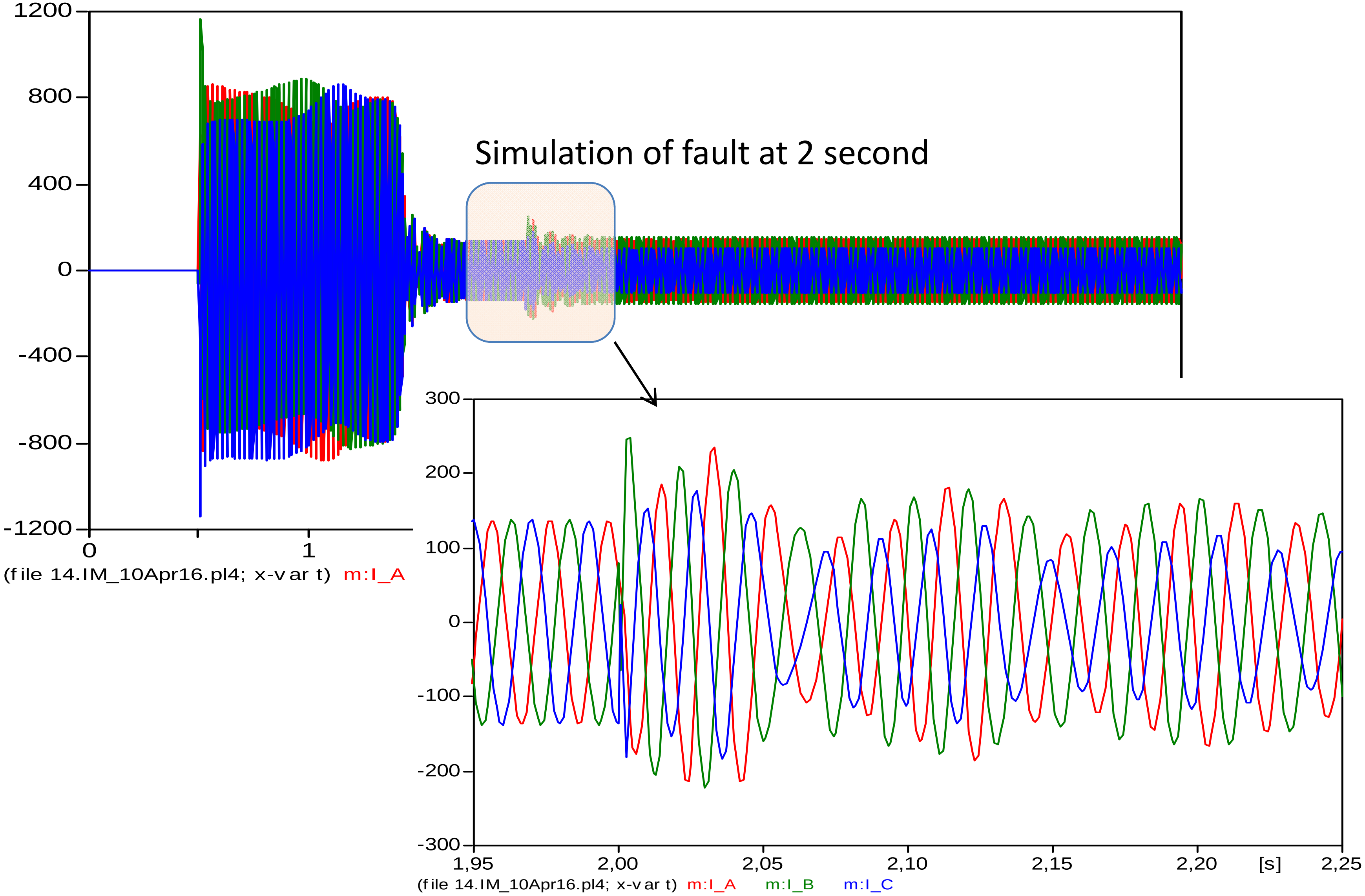






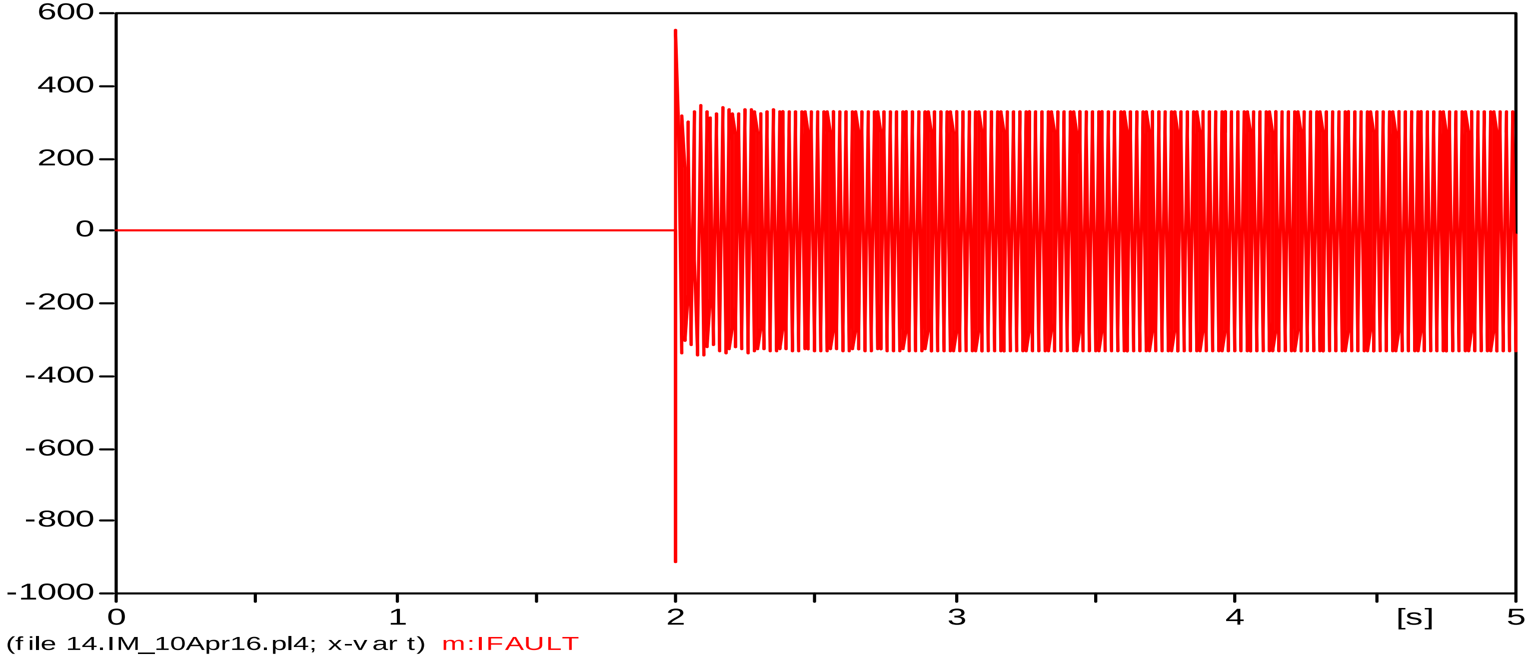


O/P – PHASE CURRENTS



Simulation of fault at 2 second

O/P – FAULT CURRENT



- Large circulating current in the faulty portion
- Faulty portion acts like autotransformer
- Terminal Current is not affected much
- Fast progression in turn-turn fault

TESTING

CHOICE OF PROTECTIVE FUNCTIONS

Recommended protection for medium voltage motors:

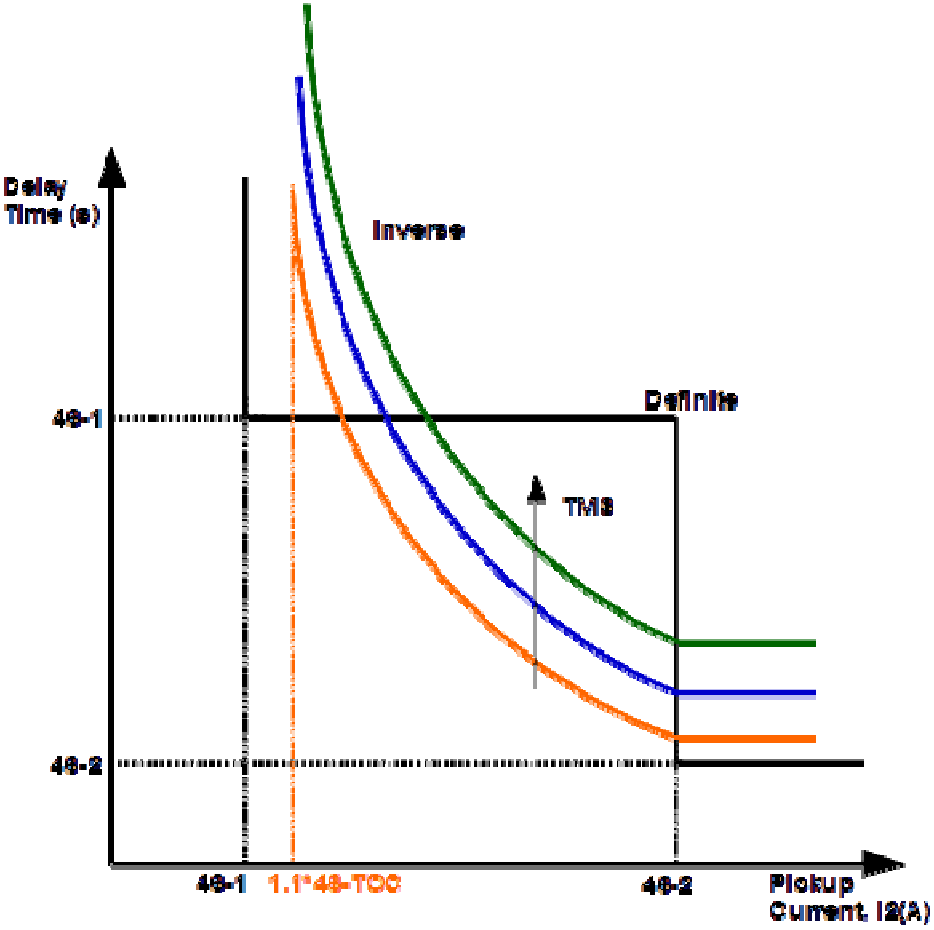
Protective Function	**ANSI**
Time-Overcurrent protection (Phase/Earth)	50,51,50N,51N
Directional earth-fault detection	67N, 51Ns, 59N
Thermal overload protection	49
Starting time supervision	48
Restart inhibit for motors	66, 49R
Negative-sequence protection	46
Undervoltage	27
Temperature monitoring	38

Selection of protection for testing turn-turn faults:

- Negative-sequence protection & Time-Overcurrent protection
- Testing of relay settings to avoid false tripping and correct tripping for turn-turn faults

Source: *Optimum Motor Protection with SIPROTEC protection relays, SIEMENS*

NEGATIVE SEQUENCE PROTECTION (46)



Pickup Setting

$$I_2 = \left(\frac{I_{2,allow}}{I_{Nom}}\right) * I_{Nom} * \left(\frac{I_{CT}sec}{I_{CT}pri}\right)$$

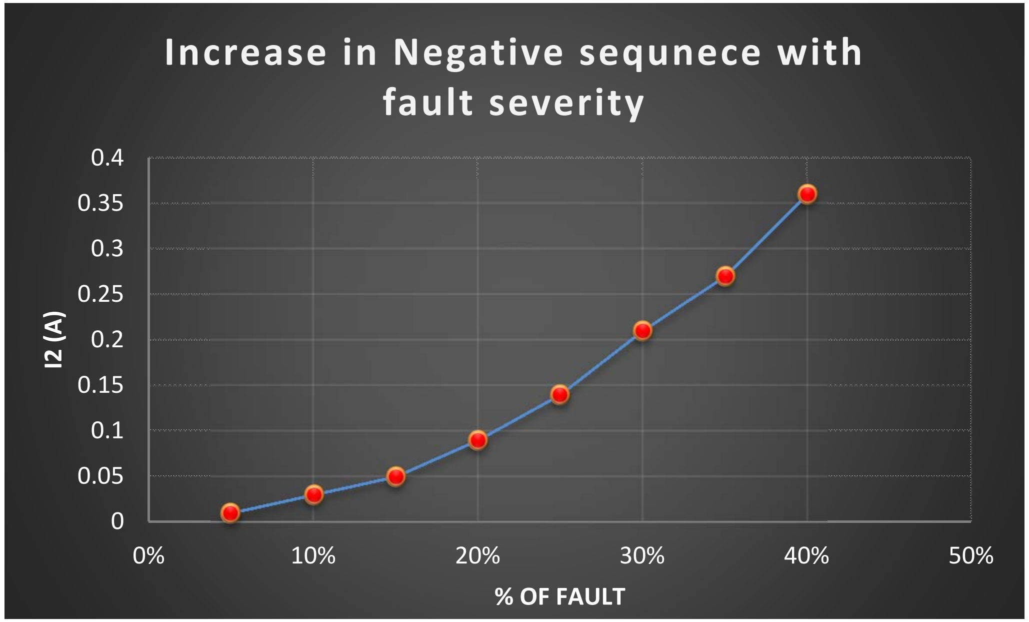
- $I_{2,allow}$ - Permissible thermal inverse current of the motor
- Inom - Nominal motor Current
- ICTPri - Primary Transformer Current
- ICTSec - Secondary Transformer Current
- ICTPri: ICTSec - 150:1 A

Parameter	Setting Options	Default Setting
46-1 Pickup	0.05.....3.00 A	0.10 A
46-1 Delay	0.00.....60.00 s	1.50 s
46-2 Pickup	0.05.....3.00 A	0.50 A
46-2 Delay	0.00.....60.00 s	1.50 s
46-TOC Pickup	0.05.....2.00 A	0.90 A
46-TOC TMS	0.05.....3.20 s	0.50 s

Source: *SIPROTEC 7SJ64 Relay* Manual

DEFINITE TIME CHARACTERISTICS

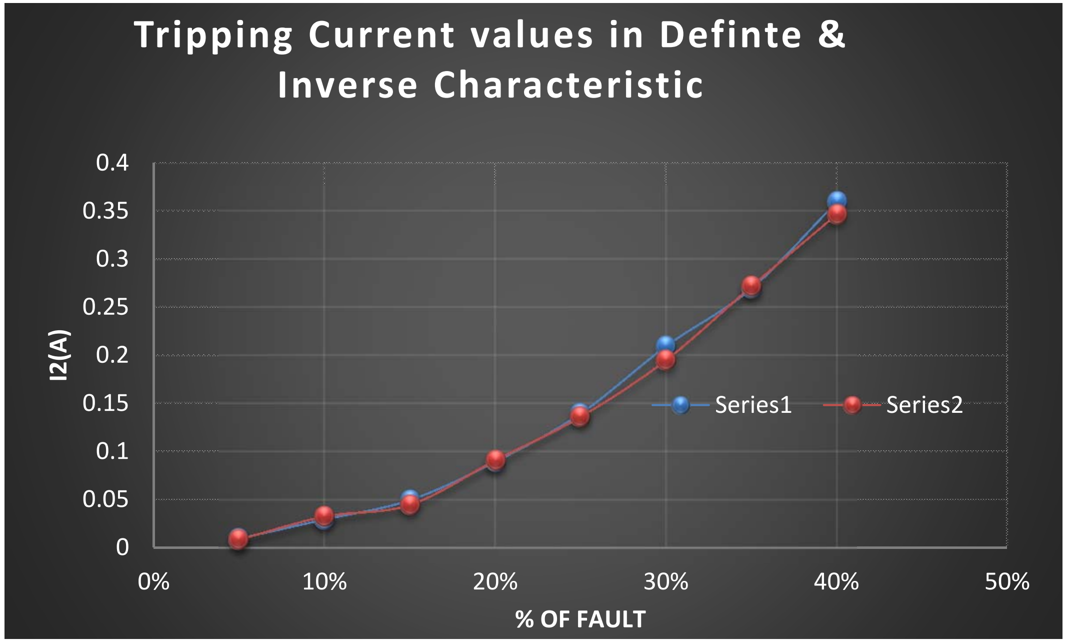
% of Faulty Turns	46-1 Pickup (A)	46-1 Delay (s)	46-2 Pickup (A)	46-2 Delay (s)
5%	*No Trip for default setting*			
10%				
15%	0,05	1,50	0,50	1,00
20%	0,09	1,50	0,50	1,00
25%	0,14	1,50	0,50	1,00
30%	0,21	1,50	0,50	1,00
35%	0,27	1,50	0,50	1,00
40%	0,36	1,50	0,50	1,00



- 2 stage Definite characteristics has been considered
- Table shows the tripping currents at recommended time setting
- Maximum tripping current (46-1 pickup) is listed for particular fault severity

INVERSE TIME CHARACTERISTICS (IEC)

% of faulty turns	46-TOC PICKUP (A)	TMS (s)	Tripping Time (s)	Negative Sequence Current ,I2 (A)
5%	*No Trip for default setting*			
10%				
15%				
20%	0,07	0,05	1,497	0,0884
	0,08	0,05	3,942	0,0876
	0,08	0,07	5,377	0,0875
	0,08	0,10	7,902	0,0874
25%	0,12	0,05	2,878	0,1368
	0,12	0,10	5,576	0,1367
	0,12	0,12	6,638	0,1366
	0,12	0,15	8,175	0,1364
30%	0,17	0,07	3,624	0,1957
	0,17	0,21	10,498	0,195
	0,18	0,05	7,77	0,1886
	0,18	0,07	10,517	0,1883
35%	0,24	0,05	2,776	0,2723
	0,24	0,11	6,47	0,2703
	0,24	0,13	7,873	0,2694
	0,24	0,17	10,515	0,2687
40%	0,31	0,05	3,171	0,3471
	0,31	0,07	4,379	0,3469
	0,31	0,09	5,598	0,3467
	0,31	0,10	6,218	0,3467



- Tripping Current value in Inverse characteristics is not different from that of Definite characteristics
- However, tripping time increases based on the choose TMS value

TMS – Time Multiplier Setting

OBSERVATIONS ON TESTING

- For approximately the same value of current in Inverse Characteristic setting, tripping time is large. This may allow high current for longer time thus heating the insulation which lead to faster propagation of turn-turn fault
- Hence, Definite Time characteristics with appropriate setting shall be applied for turn-turn fault (in case of Negative Sequence Protection)

FUTURE WORK

- Testing of Siprotec relay(7SJ645) for Time Overcurrent protection
- Compare Negative sequence protection and Overcurrent protection for turn-turn fault
- Propose a general relation between fault severity and protection parameter settings


THANK YOU!!