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Eastern Interconnection Phasor Project

Performance Requirements Task Team (PRTT)

Performance Requirements
Phase Angle Installation Issues

Task Team Leader:

Damir Novosel, KEMA

Prepared by:

Virgilio Centeno, Virginia Tech

Contributors:

Gerard Stenbakken, NIST

Henry Huang, PNNL, CERTS

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1. Glossary of Terms

This section provides some useful definitions pertinent to GPS-synchronized devices, communication protocols and communications media.

GPS – Global Positioning System. A satellite based system for providing position and time. The accuracy of GPS based clocks can be better than 1 microsecond.

Negative Sequence: A three phase sequence in which phase "A" leads phase "C" by 120 degrees and phase "C" leads phase "B" by 120 degrees.

PMU – Phasor Measurement Unit. A device that samples analog voltage and current data in synchronism with a GPS-clock. The samples are used to compute the corresponding phasors. Phasors are computed based on an absolute time reference (UTC), typically derived from a built-in GPS receiver.

Positive Sequence: A three phase sequence in which phase "A" leads phase "B" by 120 degrees and phase "B" leads "C" by 120 degrees.

Reference Angle: A measured or estimated angle which is subtracted from all angles to obtain a common reference. In a case of two angle measurement the remote angle is assumed to be the reference angle.

Referenced Angle: Angle difference obtained when the reference angle is subtracted from a given PMU angle.

UTC – Coordinated Universal Time (initials order based on French). UTC represents the time-of-day at the Earth's prime meridian (0° longitude).

2. Introduction

2.1 Brief overview of the problem

When installing a phasor measurement unit, there are several possible sources of large phase and magnitude errors due to incorrect wiring of the input signals, different phase "A" definition across utility boundaries, different input phases to the PMU, and different phasor quantities reported. Local information can be used to detect some of these errors but most errors require the use of a reference angle or additional information obtained from other properly wired devices. In this document it is assumed that error checking is performed at the control center and that the person installing the unit is in contact with the control center. Expected angle differences and magnitudes are obtained from the state estimator.

2.2 Organization of this document

This document describes some of the more common individual installation errors that may result in the measurement of incorrect phase angle differences. For each individual error symptom, explanations and corrective actions of the error are given. Compound errors are possible but to reduce confusion, the user is advised to consider the possibility of compound errors but to correct one individual error at a time and then check for additional errors.

3. Installation Phase Errors:

3.1 Incorrect voltage or current type

Symptoms:
a) Voltage magnitudes 70% larger than expected
b) Referenced voltage angles appear to be displaced by +30 degrees
c) Current magnitudes 40% smaller than expected
d) Referenced current angles appear to be displaced by +30 degrees

Corrective Action:

- Voltage inputs should be wired as line to neutral values and any line to line voltage should be rewire as line to neutral. Current inputs should be wired as line currents and any delta current should be re-wired as a line current.

Explanation:
All voltage inputs to the PMU should be line to neutral voltages and all current inputs should be line currents. A line to line voltage has a magnitude equal to 1.73 times its corresponding line to neutral voltage. A delta current has a magnitude equal to 0.577 times its corresponding line current. More important, line to line voltages and the delta

currents have their angle displaced by +30 degrees with respect to their corresponding line to neutral voltage and line current values.

3.2 Incorrect phase sequence

Symptom:
Zero or close to zero magnitude of the positive sequence phasor while the magnitude of the individual phases is not zero.

Corrective Action:
- At substation, identify phase "B" and "C" and swap their connection.
- Check for correct phase "A" determination.

Explanation:
PMUs are set to compute positive sequence phasors out of three phase signals normally labeled "A", "B" and "C". The positive sequence is obtained by rotating the phase "B" phasor by 120 positive degrees, rotating the phase "C" phasor by 120 negative degrees, adding the two results to the phase "A" phasor, and dividing the result by three, Figure 1.

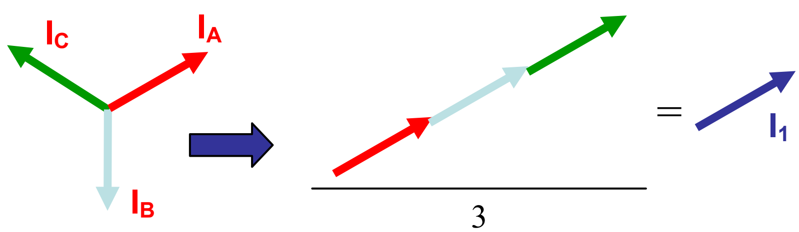

Figure 1, Positive Sequence Phasor Calculation

In a perfectly balanced system and for a correctly wired unit the result of these operations is a phasor equal to the phase "A" phasor. Any error in the identification of the system phases will cause two of the phases to be connected incorrectly. If this happens the three phase system will be wired as a negative sequence to the PMU and the signal will be filtered by the positive sequence algorithm resulting in a zero or close to zero magnitude.

This installation error does not need remote information for its diagnosis. Most PMUs provide information on the magnitude of the positive sequence phasors and the magnitude of the individual phase signals. If the magnitude of the positive sequence phasor given by the PMU display is zero but the magnitude of the individual phases is not zero, an incorrect sequence wiring is the most likely cause.

3.3 Incorrect phase "A" determination

Symptoms:
a) Referenced voltage phase angle is close to ± 120 degrees from the expected angle.
b) Disagreement between the real power flows and the measured angle differences. Power always flows from the high angle to the low angle.

Corrective action:

- For a positive angle difference, input signal should be re-wire to rotate phase "C" to "A", "A" to "B" and "B" to "C".
- For a negative angle difference, input signals should be re-wire to rotate phase "A" to "C", "B" to "A", and "C" to "B".

Explanation:
Phase "A" is usually known at the substation and it should be properly wired. If for any reason phase "A" is mistaken for one of the other phases the positive sequence algorithm will be computed with respect to the incorrect phase "A". If phase "B" is wired as phase "A", with the correct phase sequence, a phasor with an error of negative 120 degrees will be computed. If phase "C" is wired as phase "A", with the correct sequence, the computed phasor will have a positive 120-phase shift.

It has been noticed that utilities may have their own definition of phase "A" in their respective service areas. This different phase "A" definition will introduce phase shift in the positive sequence calculation as stated above. PRTT conducted a survey among utilities to determine the phase "A" relationship. An example phase "A" map is shown in Figure 2. There is a need to complete this map so it can be used as a reference. With more and more PMUs deployed in the Eastern Interconnection, more and more wide-area phase angle measurements become available and such a phase "A" reference is an important tool in assisting wide-area data analysis. Further information about this survey can be found in Appendix I.

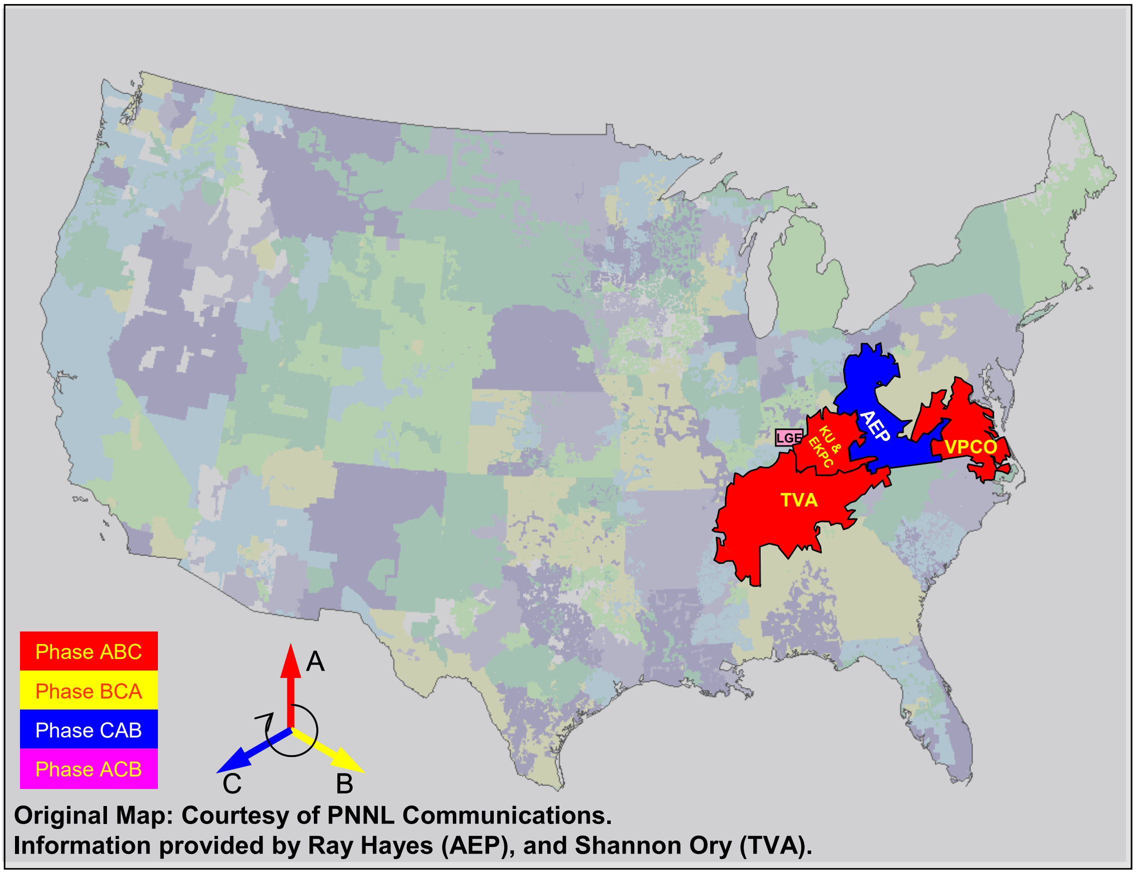

Figure 2, Example phase "A" map of the Eastern Interconnection

3.4 Incorrect Polarity:

Symptoms:

a) Referenced Angles appear to be 180 degrees out of phase

b) Incorrect agreement of locally referenced current angles with measured real and reactive power flows. (Real and reactive flows not measured by the same unit)

Corrective Action:

- Polarity of all connection should be checked and re-wire if an error is found or suspected.

Explanation:

In the unlikely case that a signal is wired with the wrong polarity, the magnitudes of the phasors will show the correct values but the referenced angles will be 180 degrees out of phase. Any real or reactive flow computed with an incorrectly wired voltage or incorrectly wired current will give real and reactive flows in opposite direction to the actual flows.

3.5 Delta-Wye transformation in the instrument transformers:

Symptoms:

a) Phase angle degrees of 30 or -30 degrees.
b) Phasor magnitudes 73% higher than expected.
c) Phasor magnitudes of 58% smaller than expected.

Corrective Actions:

- The primary wiring of the instrument transformers should be compared with the wiring of the secondary input to the PMU. Primary and secondary windings should be wired in the same type of connection, delta-delta or wye-wye.
- A 73% higher than expected magnitude indicates a wye primary and a delta secondary connection which will also result in a positive 30-degree phase shift.
- A 57% smaller than expected magnitude should be accompanied by a negative 30-degree phase shift and indicates a delta connected primary and a wye connected secondary.

Explanation:
In the rare case of a delta-wye transformation in three phase instrument transformers, a phase shift of 30 degrees and a magnitude error factor of square of root of three (1.73) will be observed in the measured three phase signal. Delta-Wye transformation are used to obtained specific signals for relaying operations but are not needed for PMU measurements. The PMUs assume phase to neutral voltages and line currents as input signals.

4. Non Wiring Errors

4.1 System phase shifts

Symptoms:
a) Phase angle degrees of 30 or -30 degrees.
b) Phasor magnitudes 73% higher than expected.
c) Phasor magnitudes of 58% smaller than expected.

Action:
This error should be documented and corrected only at the data concentrator or application program.

Explanation
Transformers at the substation may be wired with a delta-wye or wye-delta transformation. This transformation will result in an error factor of square root of three in the magnitude and the 30-degree shift on the angle between primary and secondary signals. For PMU signals all voltage inputs should be phase to neutral voltages and all currents should be line currents.

4.2 Unbalanced System

Symptoms:

a) Small magnitude errors
b) Small angle oscillations

Action:
This error should be documented but no action should be taken.

Explanation
Magnitude unbalance results in magnitude errors and negative sequence components in the signal. A 10% unbalance in one phase results in a 3.3% magnitude error in the computed Phasor. State estimator values are computed with single phase measurements and may not be affected by the unbalance. Unbalance input also results in a small negative sequence component that shows as a small oscillation in the angle.

5. Recommendations

5.1 Phase Angle Error Documentation

Most phase angle errors can be identified locally by data users, as summarized in this document. To facilitate error correction and for reference purposes, phase angle errors identified by individual users should be documented and collected at a central location. Given the transition of the phasor measurement efforts in North America, NERC as ERO would be a natural organization to serve as such a central location.

5.2 Phase "A" Mapping

Phase "A" Mapping is an important step to ensure the consistency of phase sequence among phasor measurements across a wide-area power grid. All kinds of phase sequences (ABC, BCA, YZX, etc.) are found during the PRTT process of collecting phase information from utility companies. However the efforts to develop such Phase "A" Mapping are not trivial. The PRTT recommends NERC as ERO to take the leadership collecting phase information from utility companies and completing the Phase "A" Mapping using the example presented in this document. The final mapping can be a map as shown in Figure 2 or a table as Table 1.

6. Quick Reference Chart for Wiring Errors

Symptom	Probable Cause
Incorrect Phase angle Apparently correct Magnitude	
± 30 degree phase shift	Incorrect Signal type Delta Wye Transformation
± 120 degree phase shift	Incorrect Phase "A" determination
180 degree phase shift	Incorrect Polarity
Incorrect Phase angle and Incorrect Magnitude	
± 30 degree phase shift	Incorrect Signal type Delta Wye Transformation
Close to Zero or Zero Magnitude of Positive Sequence phasor	Incorrect Phase Sequence

7. Appendix I: Phase "A" Mapping of Some Eastern Interconnection Utilities

Table 1 summarizes the survey results of phase mapping among some Eastern Interconnection utilities. Please note this is not a complete list but provided to serve an example. The contents in this table shows the phase connection between a utility and TVA, as shown in Figure 3.

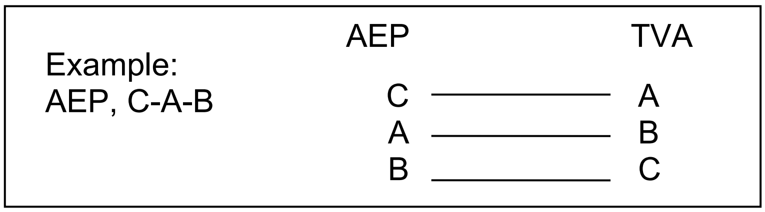

Figure 3, Interpretation of the contents in Table 1

Table 1, Phase "A" Mapping of Some Eastern Interconnection Utilities with respect to TVA's phasing*

Utilities	Phase definition in relation to TVA's A-B-C
AEP	C-A-B (3-1-2)
AEP 46kV	C-A-B and 30º lag
ALTE	C-A-B
ALTW	B-C-A
AMRN	C-A-B
CIL	C-A-B (345 kV and 138 kV); C-B-A (69 kV)
Cinergy	C-A-B
Commonwealth Edison	C-A-B
CWLP	C-A-B
Duquense	A-B-C
EKPC	A-B-C
Entergy	B-C-A
Exelon: Philadelphia Electric	B-C-A
FE: Ohio Edison	C-A-B
FE: Cleveland Electric Illuminating	B-A-C
FE: JCP&L	B-C-A
FE: METED	B-C-A
FE: Penelec 345kV, 230 kV	Z-X-Y (C-A-B)
FE: Penelec 500KV	B-C-A
FE: Penn Power	C-A-B
FE: Toledo Edison	C-A-B
IP	C-A-B
KU	A-B-C
LGE	A-C-B
MEC	B-C-A (2-3-1)
Niagara Mohawk	B-C-A
NIPSCO	C-A-B
NYSEG	B-C-A

PP&L 500kV	B-C-A
PSE&G	2-3-1 (B-C-A)
Virginia Power	A-B-C
VPCO	A-B-C
WEC	C-A-B
West Penn	B-A-C

*Source: Shannon Ory (TVA), Ray Hayes (AEP), David Schooley (ComEd), and David Barber (FirstEnergy).