CIGRE GOTF 2019 - Phase Angles as a Proxy for Voltage Stability

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Agenda

- AEP Overview
- Highpoints of AEP 2016 CIGRE GOTF paper on TVSI voltage stability.
- Phase Angles as a Proxy for Voltage Stability
- Conclusions
- Appendix – Voltage Stability Triangle Program

AEP Overview

2018 COMPANY OVERVIEW

Number of Employees	17,582
Regulated & Competitive Customers	5.8 million
Service Territory	200,000 square miles
Total Revenues	$16.2 billion
Capital Investments	$6 billion
Cash Dividends Per Share	$2.53
Transmission	40,000 miles
Distribution	220,000 miles
Total Generating Capacity (owned & PPA)	32,000 MW
Total Renewable Portfolio*	5,272 MW
Total Assets	$68.8 billion
Charitable Giving	$25.5 million

* Includes expected capacity as of year-end 2019.

https://www.aepsustainability.com/sustainability/reports/

Highpoints of AEP 2016 CIGRE GOTF paper on TVSI Voltage Stability

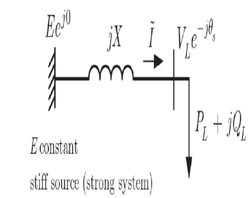
Highpoints of AEP 2016 CIGRE GOTF paper

- IEEE/CIGRE Joint Task Force Classification of Power System Stability
  - Long Term Voltage Stability using static analysis
- Triangle Voltage Stability Index – TVSI
  - Uses ratio of V_l and V_u
  - TVSI = V_l / V_u
- Next two slides demonstate V_l , V_u , and TVSI

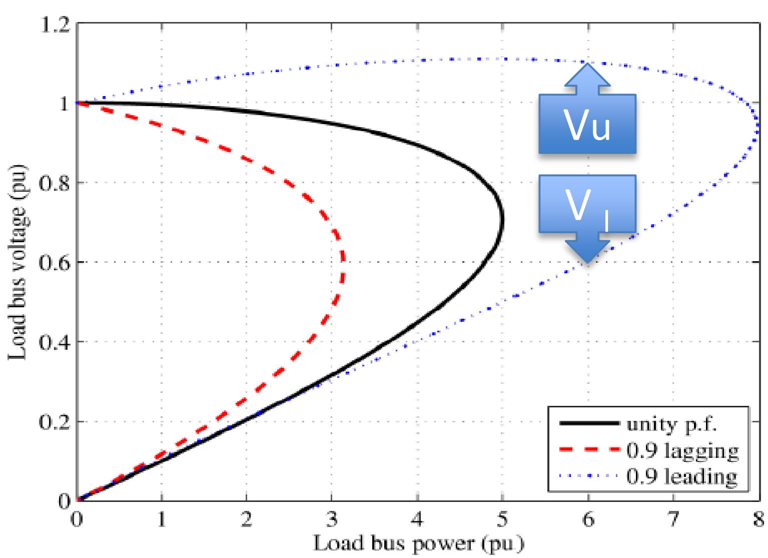
Highpoints of AEP 2016 CIGRE GOTF paper

PV Curves and Angle Separation

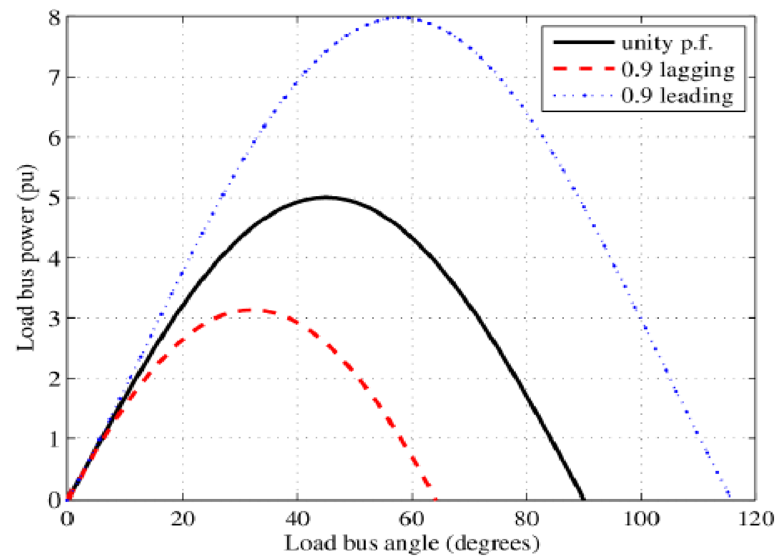
Single-Load, Stiff Bus System



- Single-load VSA with constant power factor:
- Load bus angle (angle separation) is seldom analyzed in VSA



PV Curves



Power vs. Angle Separation

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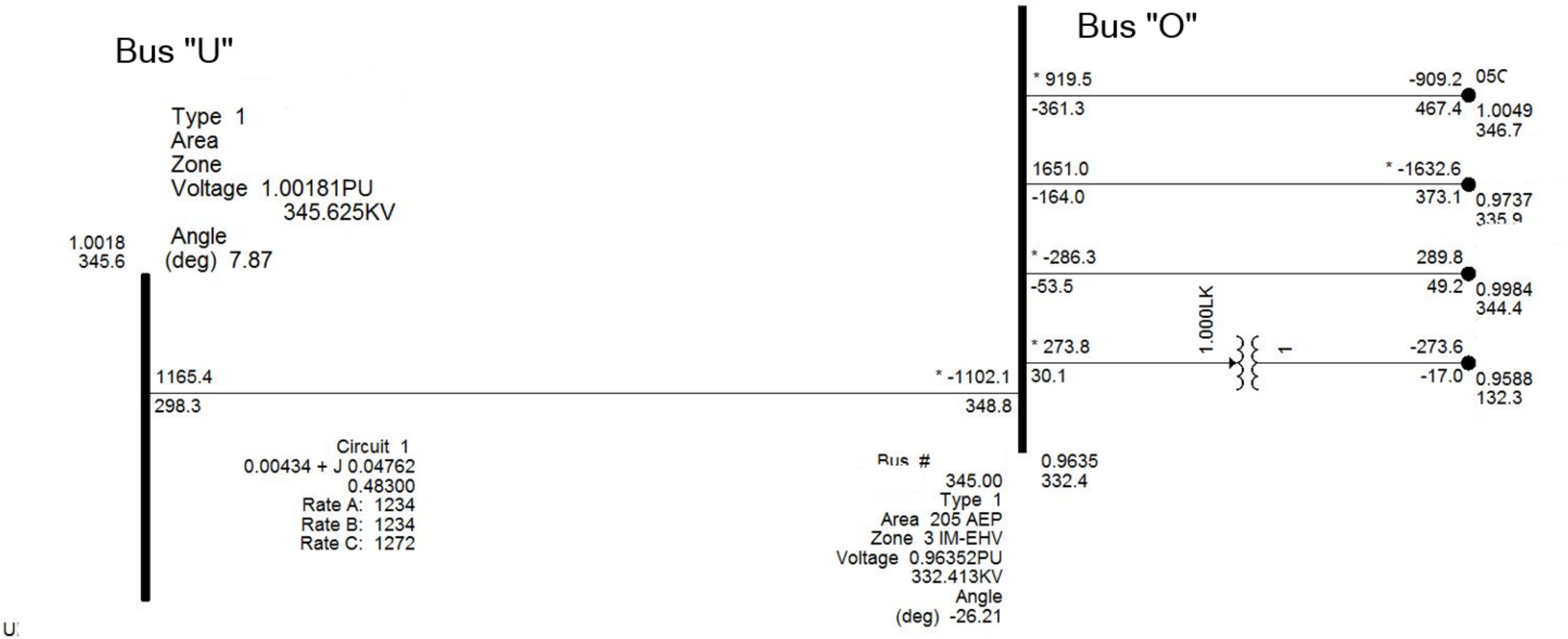
TVSI, Voltage Drop, & Phase Angle Across a Branch



What's the voltage drop across the O -U 345kV path?

1. 345.6 – 332.4 = 13.2kV?
2. 345.6@7.87 – 332.4@-26.21?

Ans: It's #2; 199kV

TVSI = V_l / Vu = 199/332.4 = 0.5987; **Delta Phase Angle** = 34.08 degrees

Phase Angles as a Proxy for Voltage Stability

Phase Angles & NERC

- NERC Standards
  - TOP 002-4 R1 has a phase angle requirement for the Operational Planning Analysis.
  - TOP 001-4 R13 has a phase angle requirement for the Real-time Assessment.
- NERC Phase Angle Monitoring technical reference document dated June 2016 notes that voltage stability and phase angles are related.

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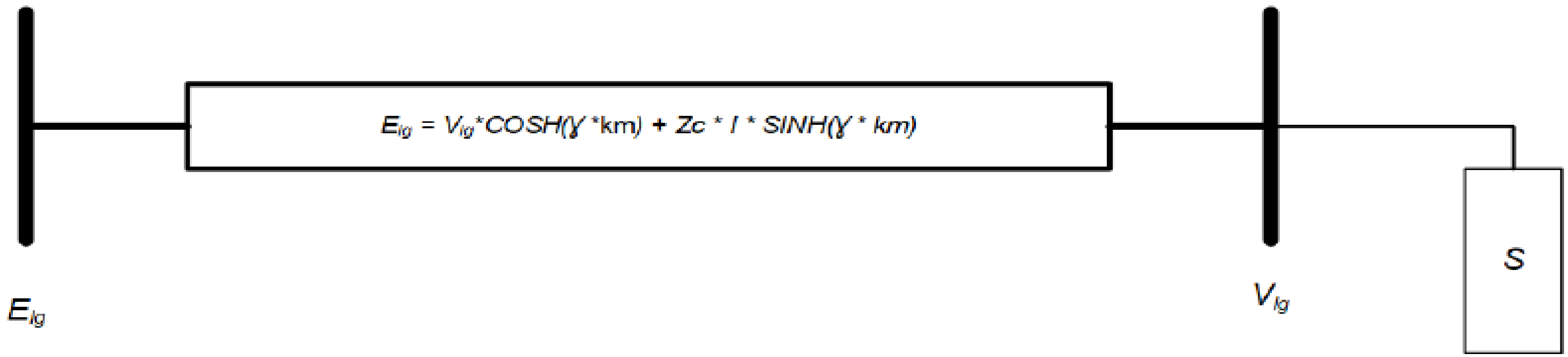
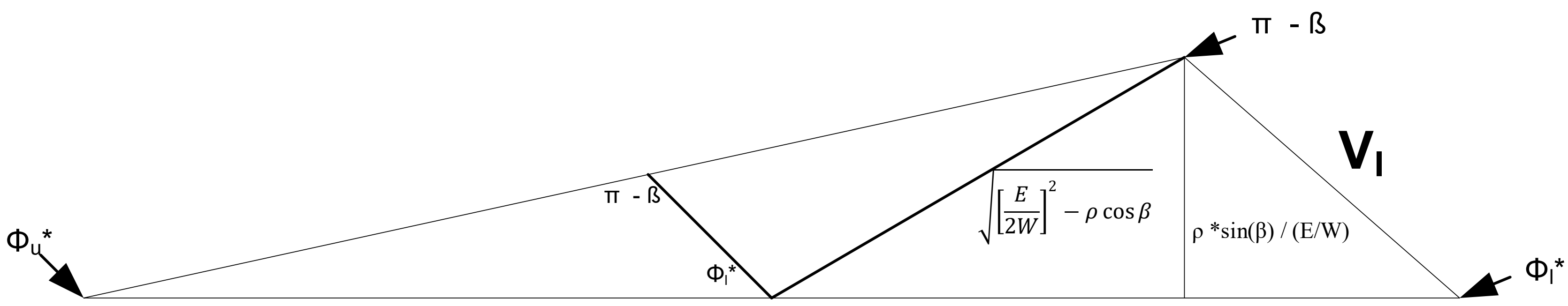
Distributed Parameter Transmission Line



- <u>**Distributed Parameter Transmission line with**</u>
  - ***E*** – Source voltage
  - ***V*** – Load voltage
  - ***S*** – Load S
  - ***Y*** – Propagation constant
  - **Z_c** – Characteristic impedance

- The next slide displays a Voltage Stability Triangle that encapsulates the distributed parameters of transmission line.
  - Use triangle to describe the voltage stability index TVSI and determine the **phase angle ϕ_u** of the load voltage V.

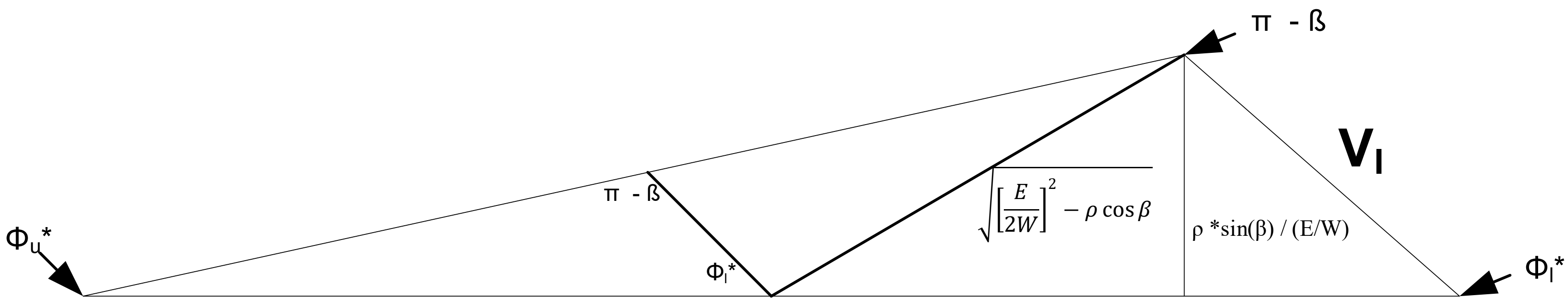
Voltage Stability Triangle



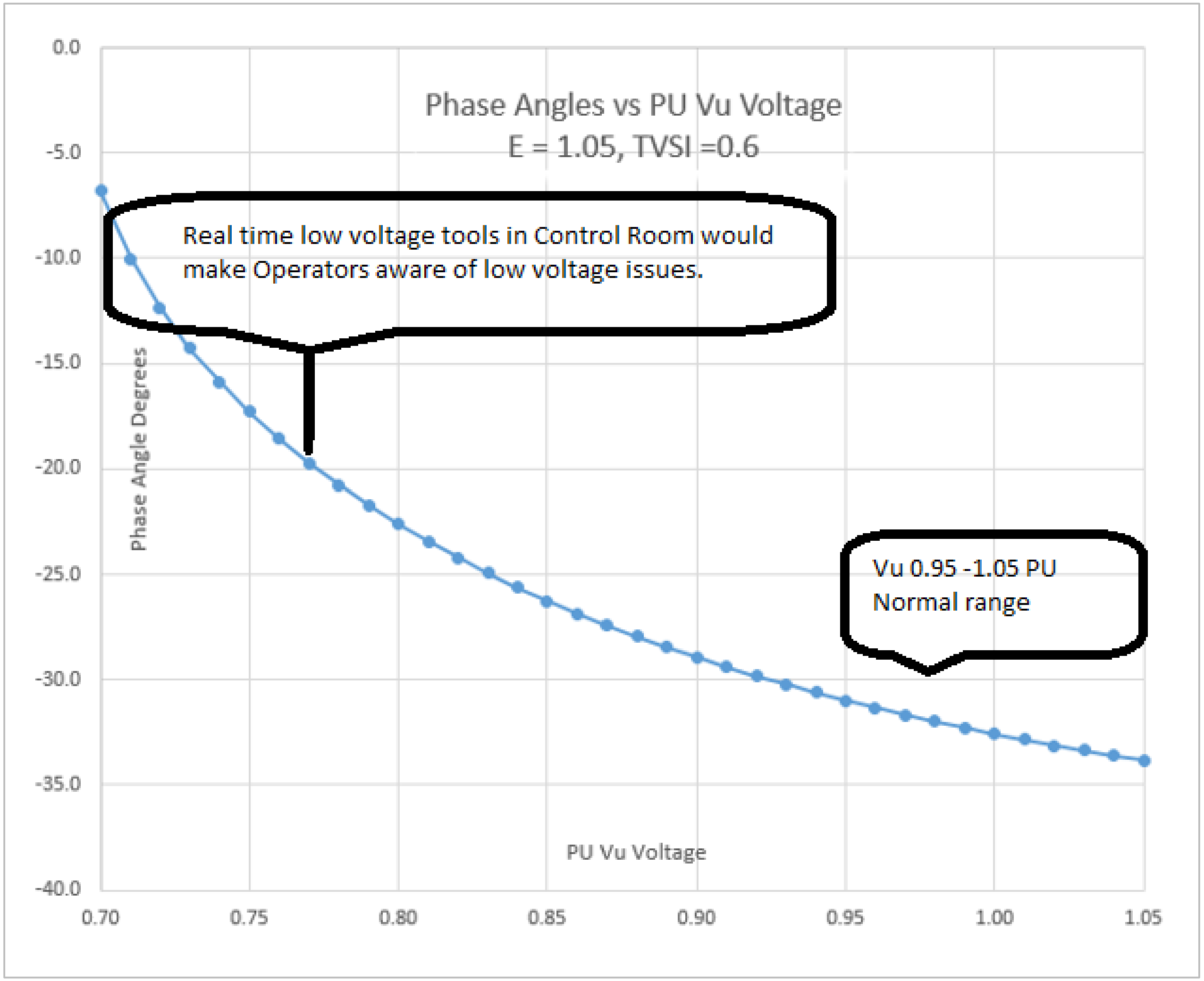
- V_u is the load voltage magnitude on the upper side of the PV curve.
  - V_l is the voltage magnitude on the lower side of the PV curve.
- The voltage stability index **TVSI** equals V_l/V_u .
  - TVSI approches 1 when we are near the apex of the PV curve.
- The **phase angle ϕ_u** is the angle of the load voltage V_u with respect to the source voltage E.
- W is a factor that elongates the source voltage.
  - For a 250km line, W elongates the voltage by about 5%.

Voltage Stability Triangle

- Use the triangle as a thinking tool.
- What is the **phase angle ϕ_u** for various V_u voltages and a given TVSI (V_l / V_u).
  - What load S drives the condition.

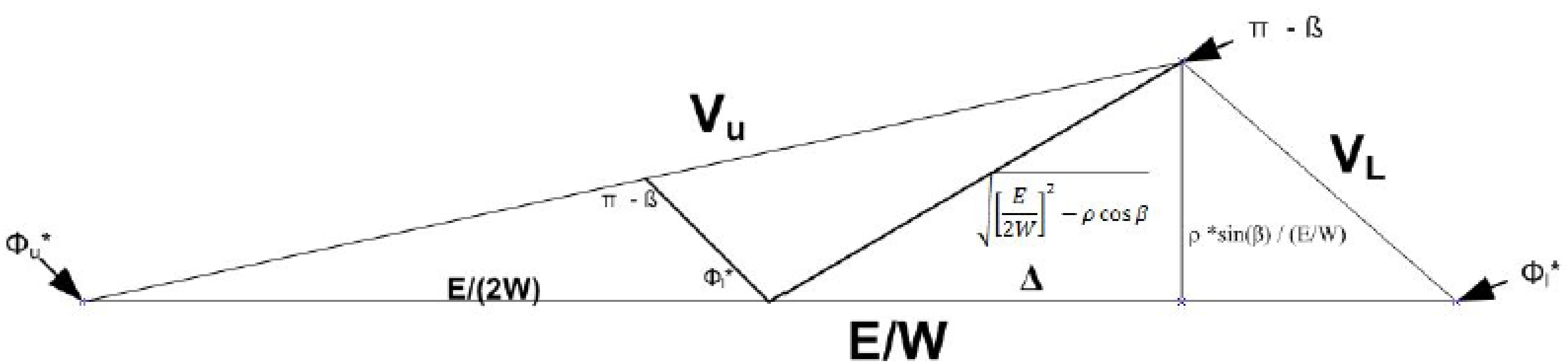


Constant TVSI and Phase Angles



Voltage Stability Triangle

- Next three slides examine **phase angle ϕ_u** associated with low voltages and normal voltages.
  - Show the associated load S.



Low Voltages, Lagging PF Load with TVSI=0.6

- 1.) Given:

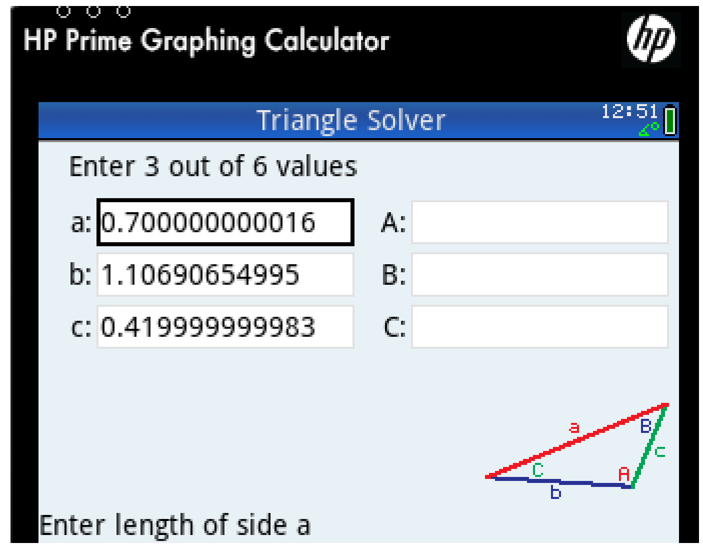
E:	1.05	KV:	345
P:	1.330807331	Q:	3.4201208886
α:	0.066/1,000	β:	1.29/1,000
SI:	285	MI:	250

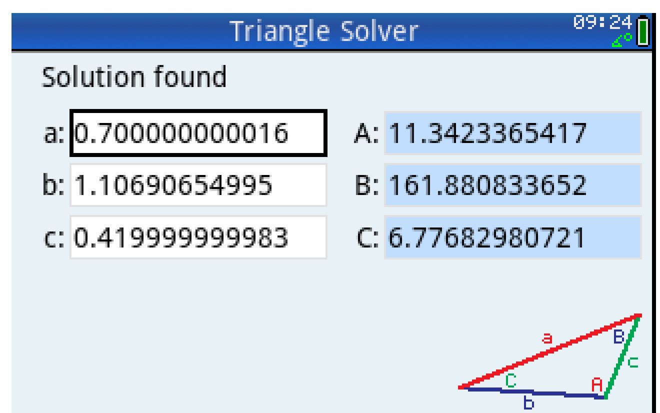
- 2.) Solve:

VOLT_TL.VU	0.700000000016∡-6.77682980664
VOLT_TL.VL	0.419999999984∡-11.3423365418
VOLT_TL.TVSI	0.599999999963

- Answer:
  ϕ_u = -6.8 degrees

- 3.) Triangle visualisation:





Normal Voltages, Leading PF Load with TVSI=0.6

- 1.) Given:

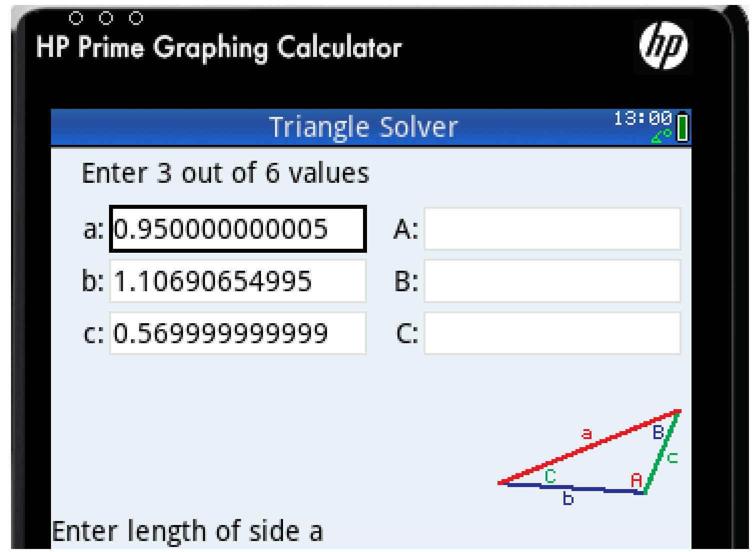
E:	1.05	KV:	345
P:	6.7484687254	Q:	−0.3839815...
α:	0.066/1,000	β:	1.29/1,000
SI:	285	MI:	250

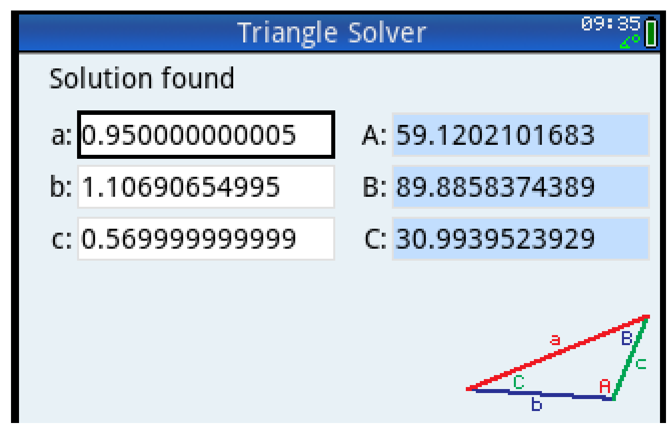
- 2.) Solve:

VOLT_TL.VU	0.950000000006∡−30.9939523928
VOLT_TL.VL	0.569999999999∡−59.1202101682
VOLT_TL.TVSI	0.599999999995

- Answer:
  ϕ_u = -31 degrees

- 3.) Triangle visualisation:





Normal Voltages, Leading PF Load with TVSI=0.6

- Bus voltages can look good and yet TVSI can be relatively high!
- **Phase angles** can provide an indication of the TVSI level for **Normal Voltages**.

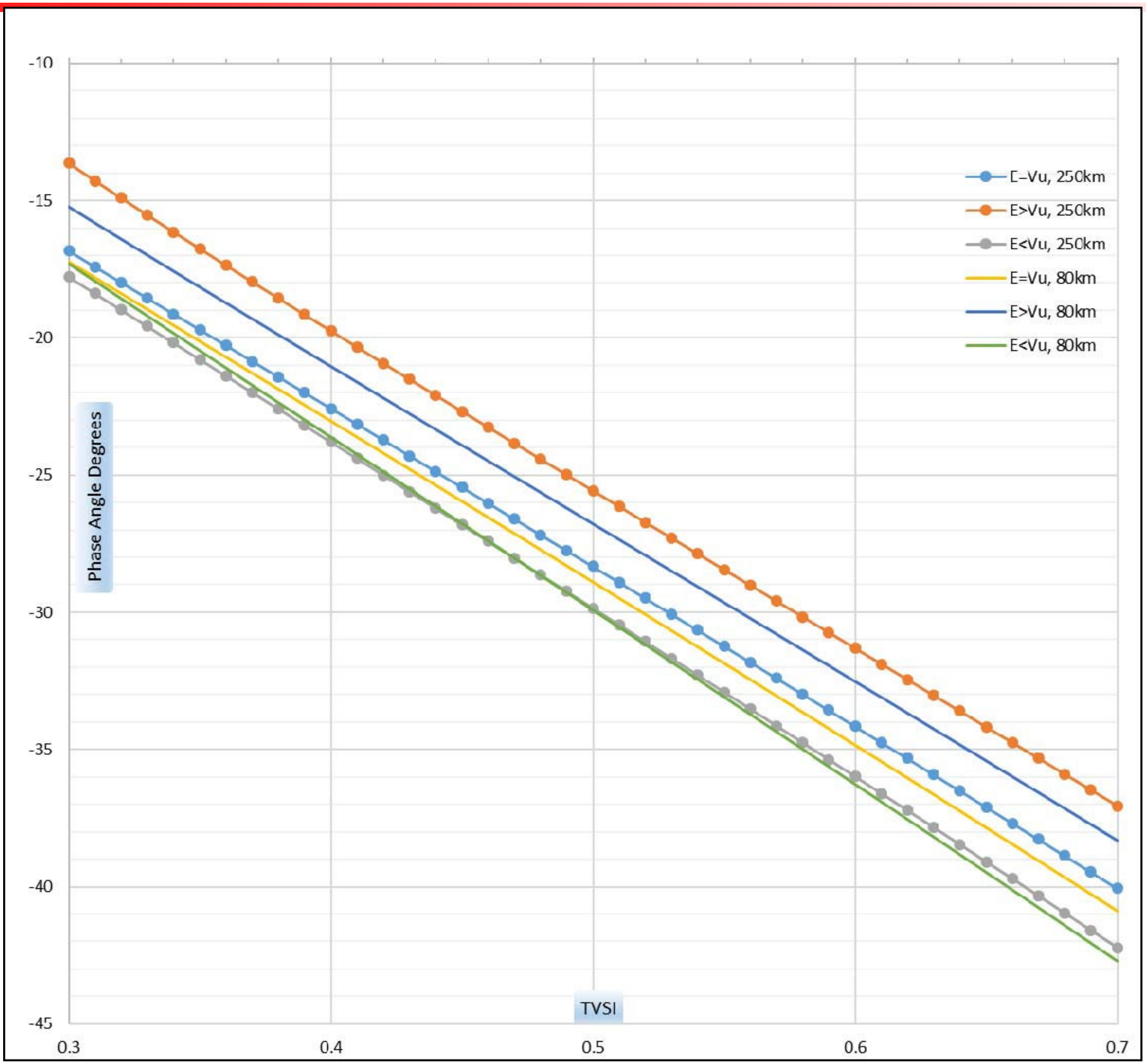
Phase Angles as a Proxy for Voltage Stability

- Existing real time State Estimator tools in the AEP control room already address low voltage magnitudes and voltage drop limitations outside the normal voltage range.
- We establish the **phase angle loci** associated with a Triangle Voltage Stability Index (TVSI) for EHV voltages in the normal range of 0.95 - 1.05PU range.
- Compare the established **phase angle** against a PSSE TVSI study.

Phase Angles as a Proxy for Voltage Stability

- On next two sides…
  - Display **Phase Angles** vs TVSI
    - 0.95 PU < E < 1.05 PU
    - 0.95 PU < V_u < 1.05 PU
      - For E=1.05 and V_u =0.95 there would be about a 10% voltage deviation.
  - Compare established **phase angle loci** against a PSSE TVSI study.

Phase Angles vs TVSI



Comparison of PSSE Phase Angles to Phase Angle Loci

PSSE TVSI Study							Phase Angle Loci for given PSSE TVSI
From bus	To bus	TVSI	BASE kV	Difference Angle in Degrees	Contingency	Case	Angle Range Degrees[2]
A	C	0.6784	138	-38.9°	N –V 345kV + L –V 345kV	2018 Summer SPA South –North transfer	-35.8°, -40.6°
N	V	0.45817	345	-26.3°	L –V 345kV + M –F 345kV	2018 Summer SPA South –North transfer	-23.2°, -27.3°
P	V	0.41695	345	-23.6°	H –S 345kV + E	2018 Summer SPA South –North transfer	-20.7°, -24.7°
N	W	0.34818	345	-19.2°	L –W 345kV + R –C 345kV	2018 Summer SPA South –North transfer	-16.6°, -20.3°
D	S	0.65237	345	-37.9°	J –R 765kV + D –E 345kV	2018 Summer SPA West –East transfer	-34.3°, -39.6°
D	S	0.53417	345	-30.7°	J –R 765kV	2018 Summer SPA West –East transfer	-27.5°, -32.1°
K	M	0.4547	345	-26.4°	C –J 765kV	2018 Winter SPA North –Southeast transfer	-23.°, -27.1°
K[1]	M	0.3805	345	-21.9°	C –J 765kV	2018 Winter SPA North - Southeast transfer	-18.6°, -22.4°

Conclusions

- AEP uses **phase angles** as a proxy for voltage stability using EHV voltages in the normal range of 0.95 to 1.05 PU to provide situational awareness to system operators on key circuits.
- Existing real time tools in the AEP control room already address low voltage magnitudes and voltage drop limitations outside the normal voltage range.

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Appendix - Voltage Stability Triangle Program

```
//HP PRIME CALCULATOR
// Transmission Long Line Load Flow
// W.D. Stevenson, Jr  Elements of Power System Analysis, 4th ed.
//  (New York: McGraw-Hill, 1982)
//  Based on VS = V*Cosh((α +jβ)*mi) + Zc*I*Sinh((α +jβ)*mi) equation in
//  Stevenson's book.
 // E - PU sending voltage
 // KV - Base KV
 // P+jQ - PU receiving load
 // α +jβ - Propagation Constant / MI
 // SI - Surge Impedance in Ohms
//Michael R Richardson 8/2/2018
//
EXPORT ET,VU,VL,ρ,VUn,VLn,Vs,Is;
EXPORT TVSI;
EXPORT VOLT_TL(E,KV,P,Q,α,β,SI,MI)
BEGIN
LOCAL VR,VI,VRL,Z,W,Ir;
HComplex:=1;
HAngle:=1;
W:=COSH((α,β)*MI);
Z:=SI*SINH((α,β)*MI) / ((KV^2/100.));

ρ:=(CONJ((P,Q))*Z/W);
ET:=E/ABS(W);
SideB:=ET;
VI:=-IM(ρ)/ABS(ET);
Δ:=ABS(ET/2.)^2-RE(ρ)-(VI^2);
IF Δ < 0. THEN
  HAngle:=0;
  RETURN "No solution Δ="+Δ;
END;
Z5:=(P,Q);

Δ:=√Δ;
VR:=ABS(ET)/2.+Δ;
VRL:=ABS(ET)/2.-Δ;
VU:=(VR,VI);
VL:=(VRL,VI);
VUn:=(VR,VI)/normalize(W);
VLn:=(VRL,VI)/normalize(W);
SideA:=ABS(VUn);
SideC:=ABS(VLn);
Ir:= CONJ( (P,Q)) / CONJ(VUn);
Vs:=VUn*W + Ir*Z;
Is:=Ir*W + VUn*SINH((α,β)*MI)*KV^2/(SI*100);
//TVSI:=ABS(VL/VU);
Z6:= Vs/Is;  //Z @ SOURCE END
Z1:=W*VUn +Z*(P,-Q)/CONJ(VUn);
Z2:=W*VLn +Z*(P,-Q)/CONJ(VLn);
Z7:=SI*SINH((α,β)*MI);
Z9:= W;  //COSH( )
TVSI:= ABS(VL/VU);
Z8:= 2*ABS(W)^2 * ABS(ρ) * (1 + COS(ARG(ρ) ) );
Z8:= √Z8;  //Ec -critical sending in voltage
HAngle:=0;
RETURN ABS(VUn)+"∡"+ARG(VUn)+" Δ="+Δ;

END;
```