Novel IBR Control by Emulating Synchronous Generator Fault Response

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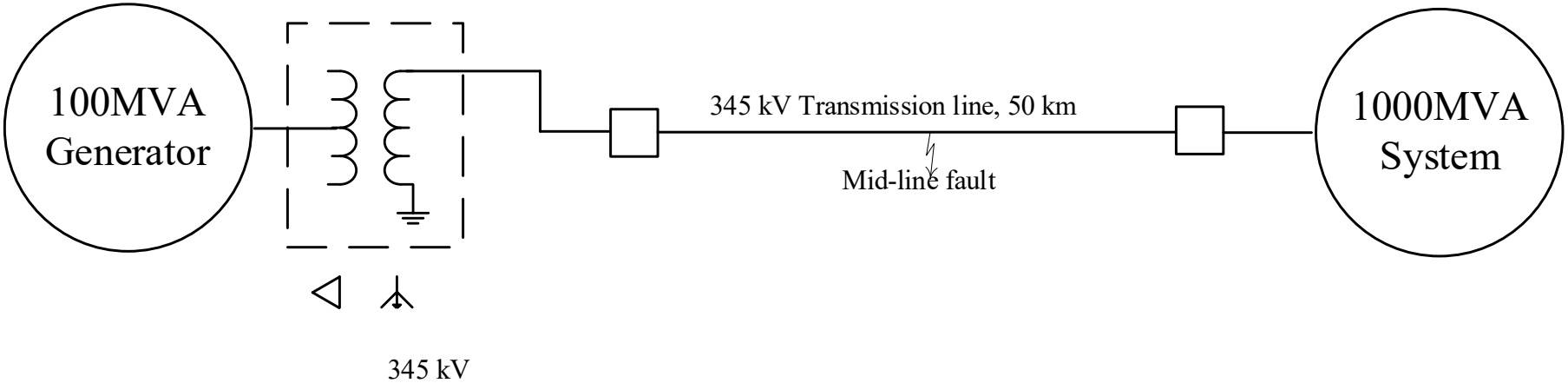
Outline

- Research Problem
- Proposed Solution
- Results
- Questions

Problem Definition

- Inverters are traditionally controlled to always produce balanced currents even during unbalanced faults.
- Distance protection need sequence quantities for proper operation.
- As IBR penetration increases, this may necessitate protective equipment replacement or redesign

Voltages and Currents during Faults – Conventional Generator

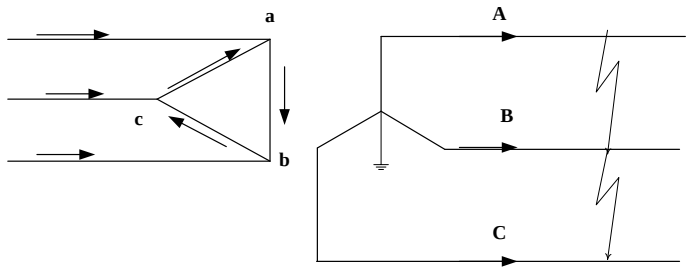


System one Line

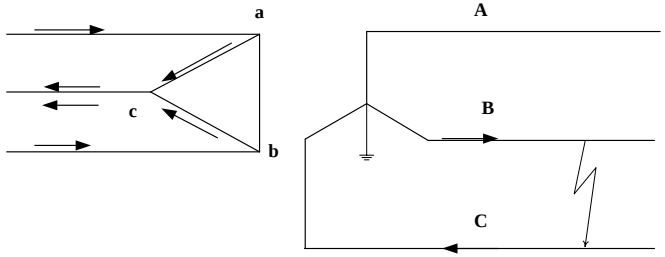
Voltage and Current relationship

- Three phase Fault: Pre-Fault Voltage V_A 1.0 PU @ 0^0

A-B-C-Gnd	A- Phase	B-Phase	C-Phase
V (PU):	0.03 @ -3^0	0.03 @-123^0	0.03 @ 117^0
Line Current	I @ -87^0	I @ 153^0	I @ 33^0
Generator Current	IG @-117^0	IG @ 123^0	IG @ 3^0



Three Phase Fault



Phase to Phase Fault

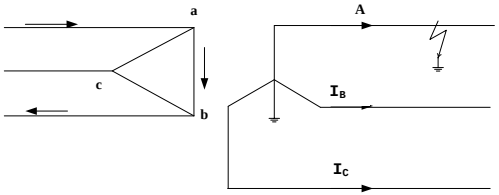
- Phase –Phase: Pre-Fault Voltage V_A 1.0 PU @ 0^0

	A- Phase	B-Phase	C-Phase
V (PU):	0.99 @ -0.3^0	0.50 @ -177.5^0	0.50 @ 176.8^0
Line Current	~0 @ 156^0	I_{LL} @ -175.6^0	I_{LL} @ 3.9^0
Generator Current	IG_{LL} @-176.6^0	IG_{LL} @ -175.1^0	$2IG_{LL}$ @ 4.1^0

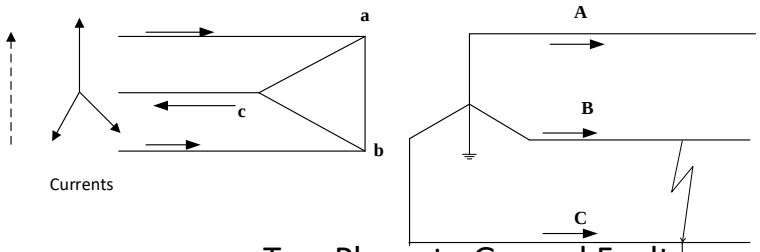
Voltage and Current relationship

- Phase to Ground Fault: Pre-Fault: Voltage V_A 1.0 PU @ 0^0

A-Gnd Fault	A- Phase	B-Phase	C-Phase
V (PU):	0.08 @ -7.2^0	0.96 @-117.7^0	0.97 @ 116.4^0
Line Current	$IA_{_LG}$ @ -85.3^0	I_{BLG} @ -84.9^0	I_{CLG} @ -86.9^0
Generator Current	IG_{LG} @-84.8^0	IG_{LG} @ 95.0^0	0 @ -113.2^0



Phase to ground Fault



Two Phase to Ground Fault

- Two Phase to Ground Fault: Pre-Fault Voltage V_A 1.0 PU@ 0^0

B-C-G Fault	A- Phase	B-Phase	C-Phase
V (PU):	0.93 @ -0.7^0	0.07 @ -166.6^0	0.07 @ 151.5^0
Line Current	IA_{LLG} @ 97.7^0	IB_{LLG} @ 142.7^0	IC_{LL-G} @ 45.5^0
Generator Current	IG_{LL} @ -146.2^0	IG_{LL} @ 153.3^0	IG_C_{LL} @ 3.7^0

Proposed Solution

1. Fault identification based on voltage magnitudes at the relay location/ at the inverter transformer terminals.

2. Modify inverter controls to change the magnitude and phase angle of phase currents to emulate sync. gen. response.

Fault Identification (345kV)

- Single Line to Ground (SLG)
  - Faulted phase to ground voltage below 0.8 pu
  - Healthy phases are above 0.8 pu
- Line to Line (LL)
  - Both faulted phase voltages below 0.8 pu, above 0.4 pu
  - Faulted line to line voltage below 0.8 pu
- Double Line to Ground (LLG)
  - Both phase voltages below 0.4 pu
  - Faulted line to line voltage below 0.8 pu
- Three Phase to Ground Fault
  - All phase voltages below 0.8 pu

Obtaining Reference Currents (A-G)

- Sync. Gen. currents on low side of Xfmr are:

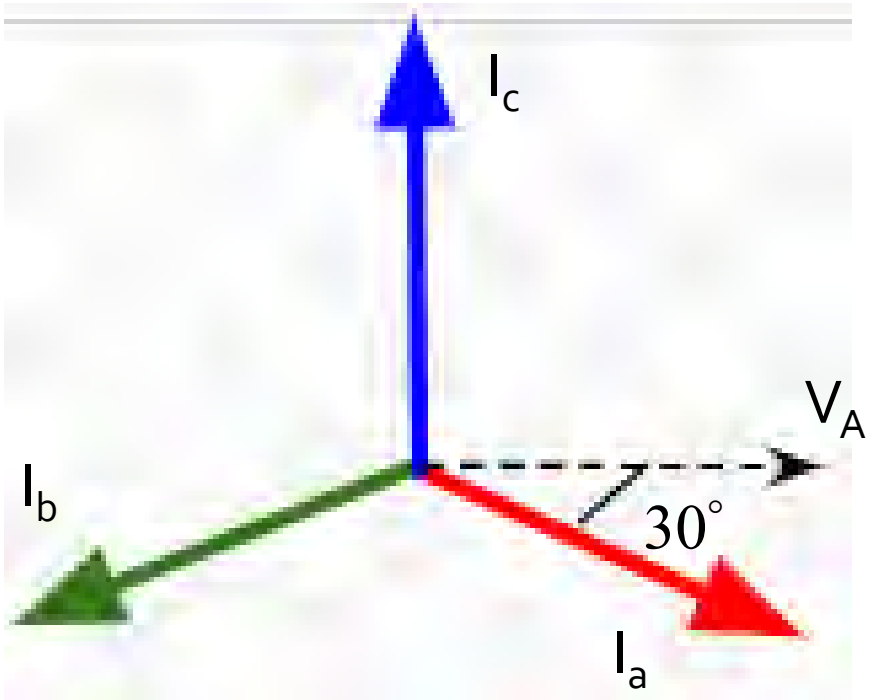
  $I_a = -I_b$; $I_c = 0$

  – Inverter current magnitude limited to 1.0 pu

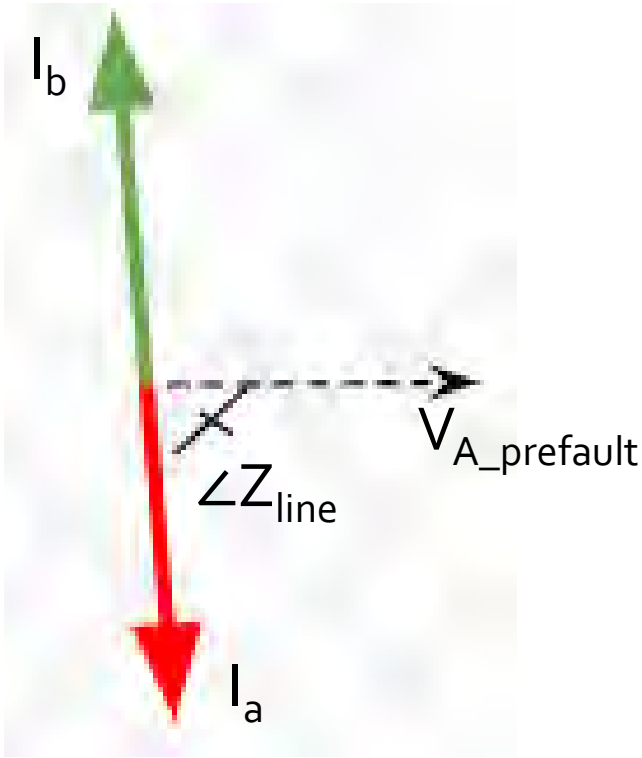
- Pre-fault V_A angle is used as a reference to specify appropriate $I_{a,b,c}$ angles

Inverter Currents (A-G Fault)

Pre-Fault



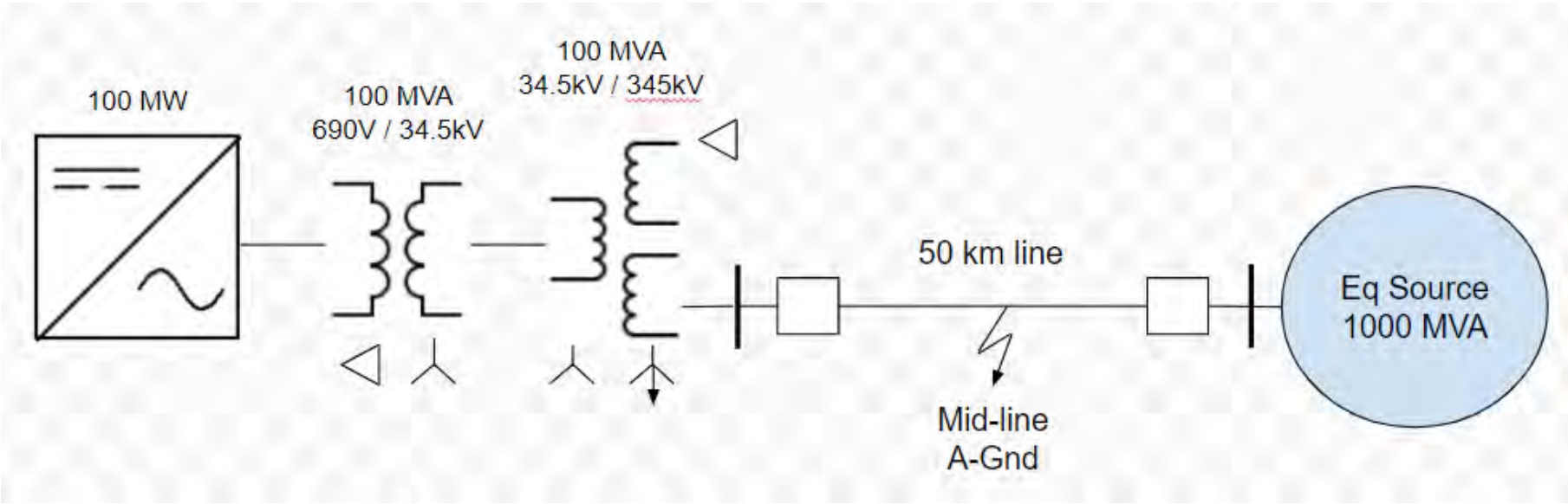
Post-Fault



Reference Currents Table

Fault	I_a	I_b	I_c
A-G	$1 \angle -85°$	$1 \angle 95°$	0
B-C	$0.5 \angle 180°$	$0.5 \angle 180°$	$1 \angle 0°$
B-C-G	$0.5 \angle -150°$	$0.5 \angle 150°$	$1 \angle 0°$
A-B-C-G	$1 \angle -115°$	$1 \angle 125°$	$1 \angle 5°$

System One-line with IBR



690V: a,b,c

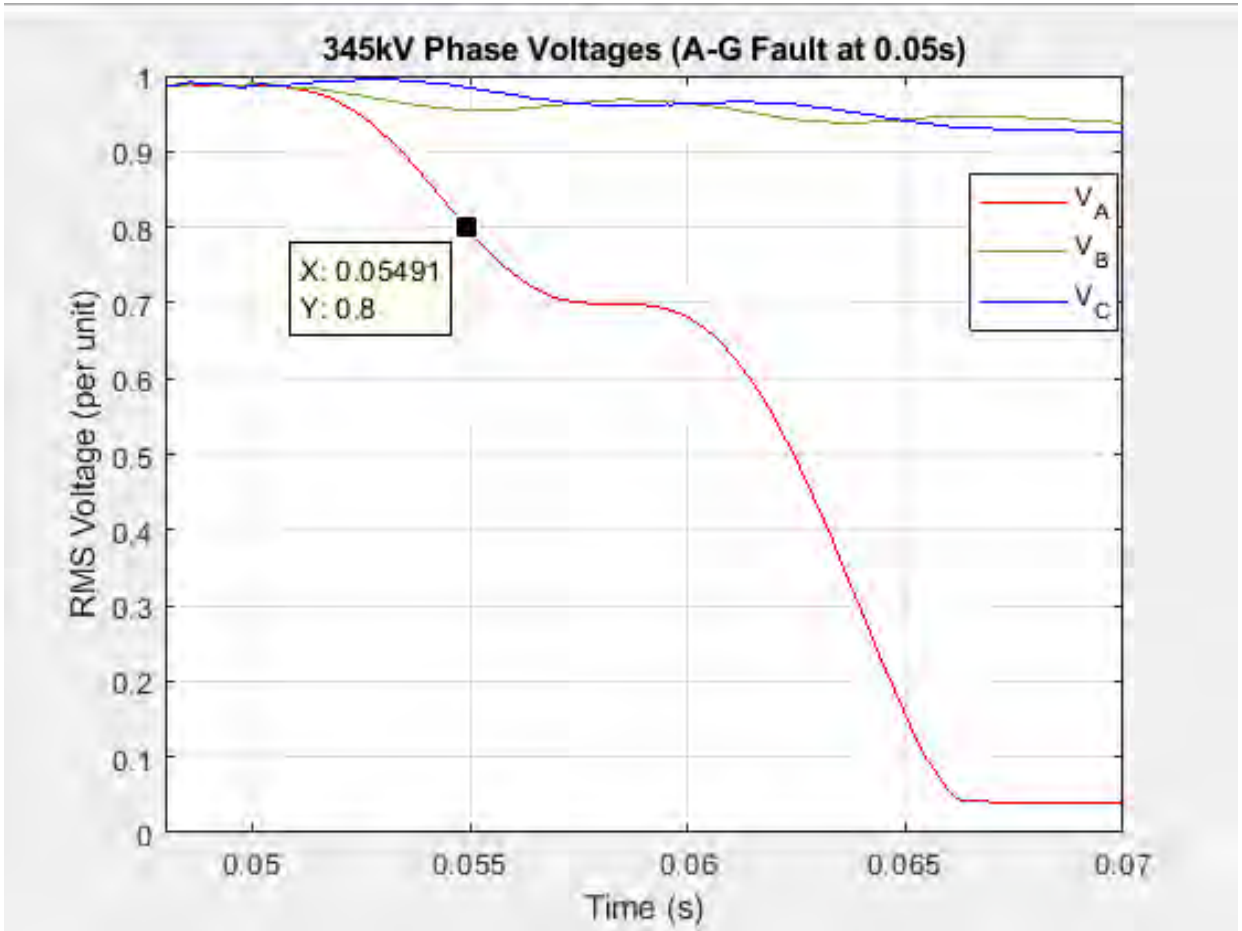
345kV: A,B,C

A-G Mid-line Fault Summary

- Fault detected
  - 1 cycle
- Inverter currents modified
  - 2 cycles
- Sync Gen behavior emulated within 3 cycles
  - I_A lags V_A by $\angle Z_{line}$

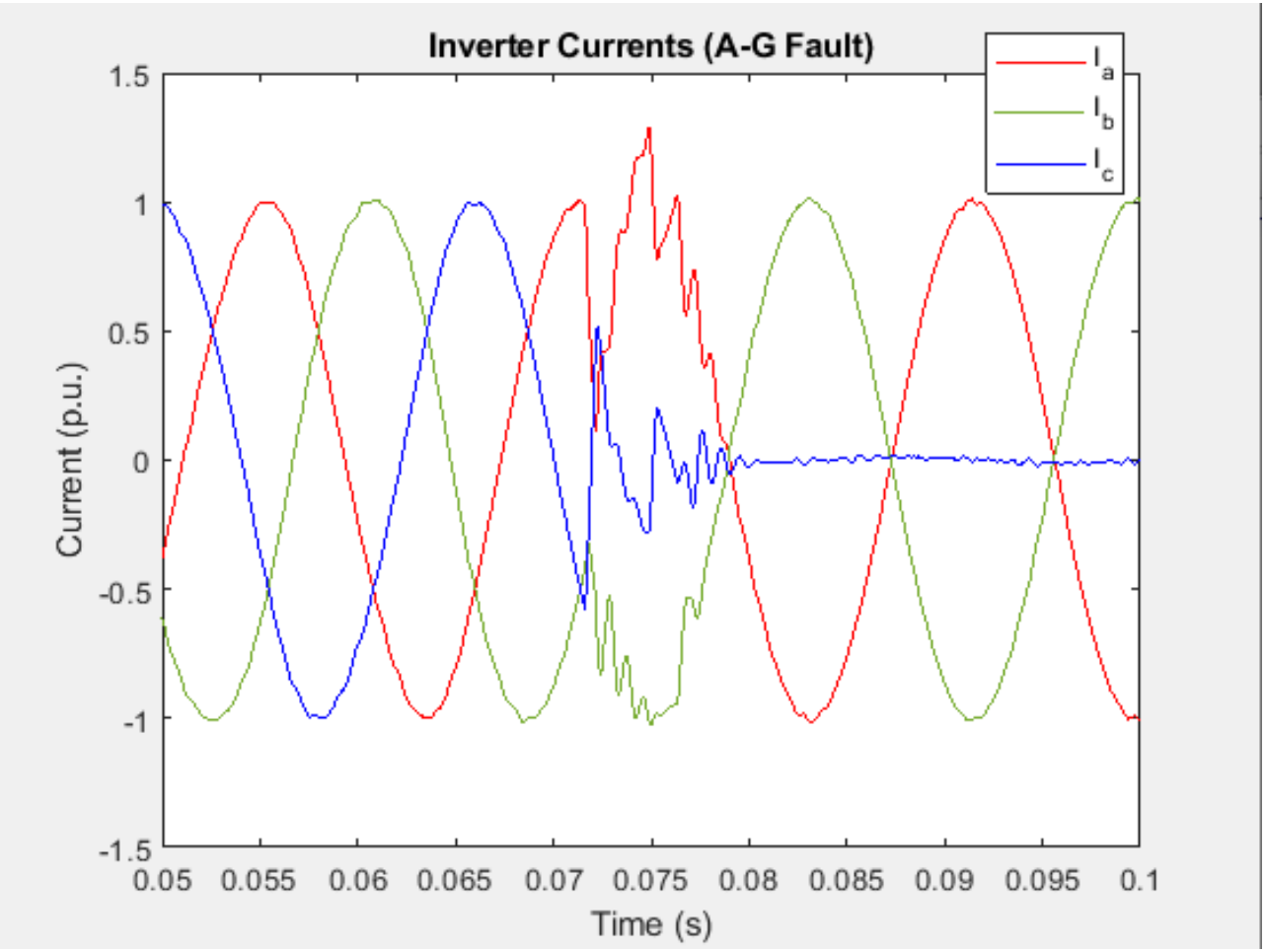
345kV Fault Detection

- A-G fault detected
  - 4.9 ms
- RMS 1 cycle moving window



Inverter Currents (690V)

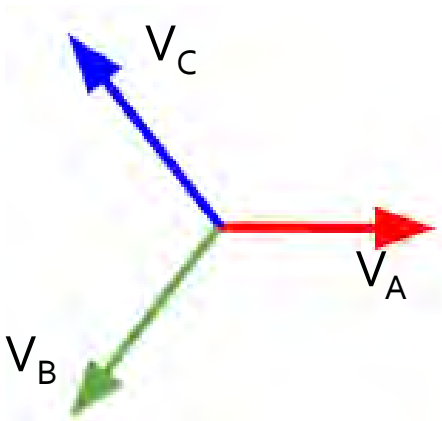
- Pre-fault Balanced
- Post-fault
  $I_a = -I_b$
  $I_c = 0$
- 29 ms



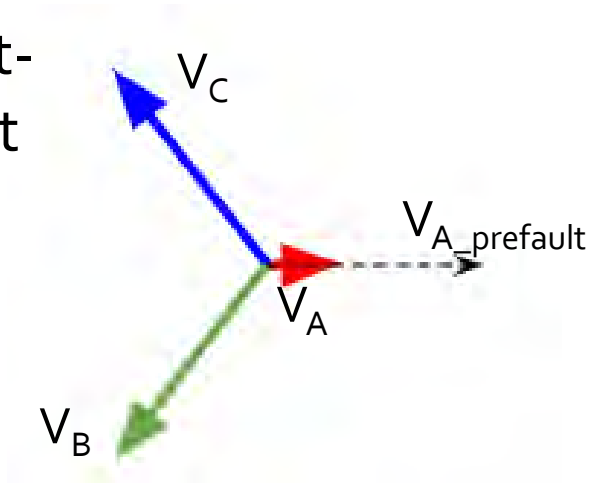
345kV Phase Voltages

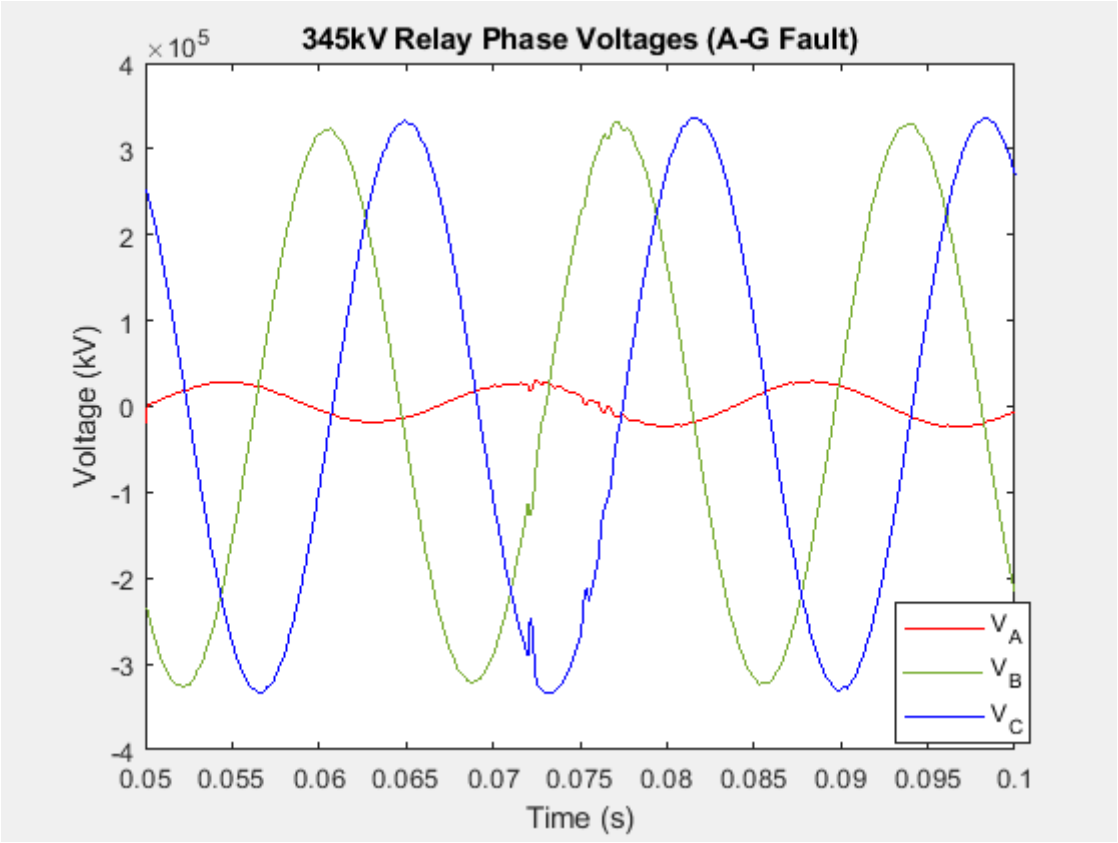
Phasors

Pre-fault



Post-fault

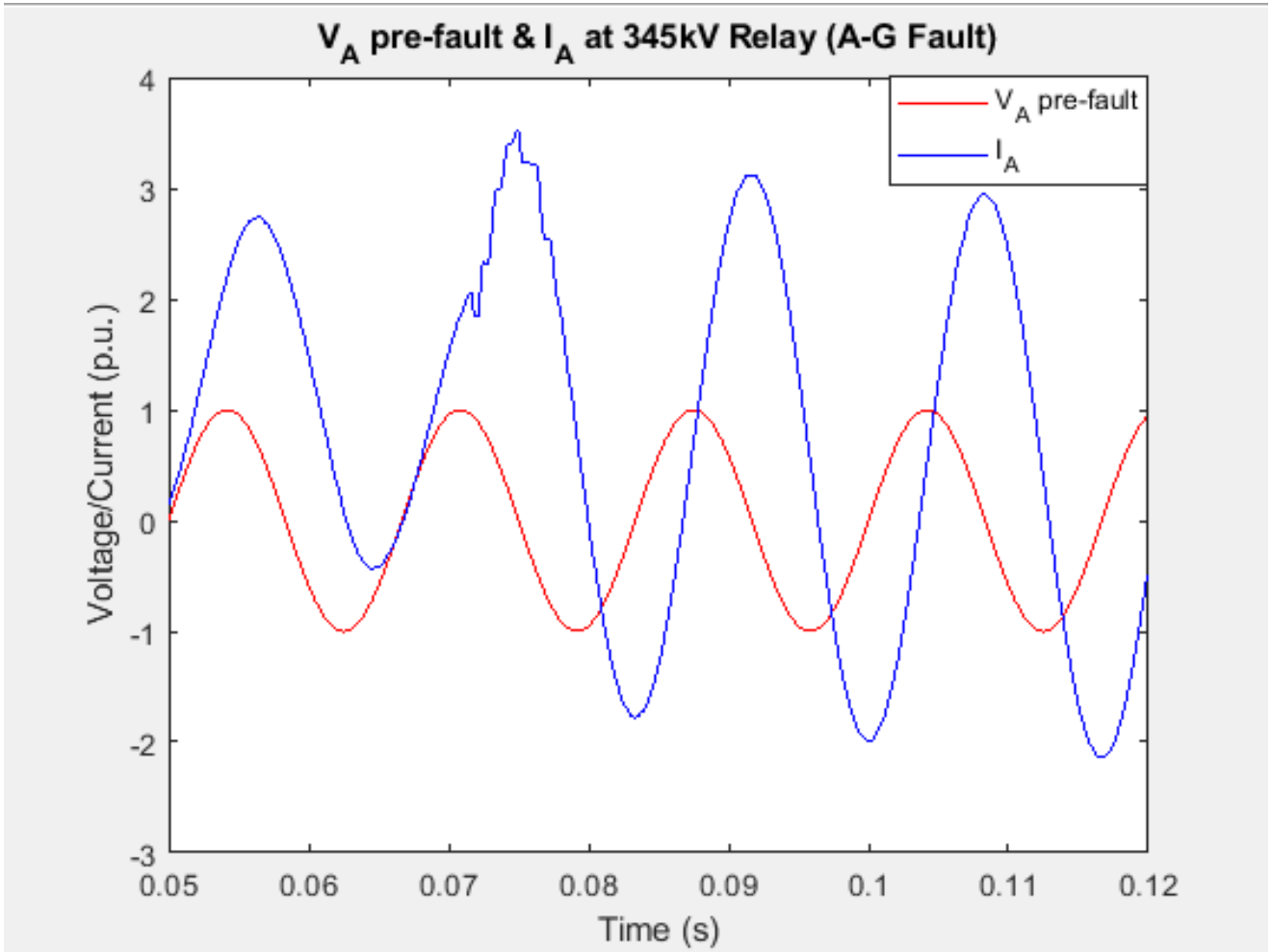




V_A & I_A Phase Relationship

I_A lags V_A by $\angle Z_{line}$ (85°)

Within 3 cycles



COMTRADE Verification

- Played back on a relay from one manufacturer

Fault Type	Mid-Line		End-Line	
	Dist. (p.u.)	Zone-1?	Dist. (p.u.)	Zone-1?
A-G	0.493	Yes	0.991	No
B-C	0.503	Yes	0.995	No
B-C-G	0.562	Yes	1.048	No
A-B-C-G	0.502	Yes	1.009	No

- Fault impedance measured properly for all fault types

Future Work

- Hardware-in-the-loop with Opal-RT
- Energy storage as a source during fault
  - During low pre-fault output
- Testing additional manufacturer's relays

Acknowledgements

NSF

Xcel Energy℠

Thank You!

- Dan Kelly
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  - Pratap.mysore@ieee.org