

# **Effective System Grounding. Analysis of the effect of High penetration of IBRs?**

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1. What is the difference between grounded and ungrounded systems?
2. What is the purpose of designing grounded systems?
3. Refresher on sequence networks.
4. What about “ground source” or “sources of zero sequence currents”?
5. Example of a grounded system
6. Example of a IBR connected to a ground system.
7. What could become problematic if the IBR do not allow for negative sequence.
8. Model simulations

1. What is the difference between Grounded and Ungrounded systems?

A **grounded system** is an electric network where **zero-sequence currents** are produced when a fault involving ground occurs.

In **ungrounded system** a phase to ground fault **produces zero-sequence voltage** and no zero-sequence current.

## 2. What is the purpose of designing grounded or ungrounded systems?

**Fault current in relation with voltage is important to allow location of the fault** on a large transmission system. No matter how large an ungrounded system is, when a phase is grounded, the entire system sees the same zero sequence voltage. **No protection can effectively isolate a small faulted section.** The only information that can be derived is that a fault is present.

In **ungrounded system** the occurrence of large zero sequence voltage causes **large overvoltage conditions during faults.** However, the **absence of current** allows the **detection of the fault occurrence without heat and flashing damage** which is very useful at lower voltage where strong sources can create high energy arc flash conditions.

**Grounded system** allows for reduction of **the overvoltage conditions which allows for lower insulation level** on equipment. This is **cost effective** on **higher system nominal voltage.**

For these reasons:

- **transmission systems are grounded** and should remain grounded
- **ungrounded systems** are suited for **high energy, small and lower voltages** application (industrial, or generator buses).

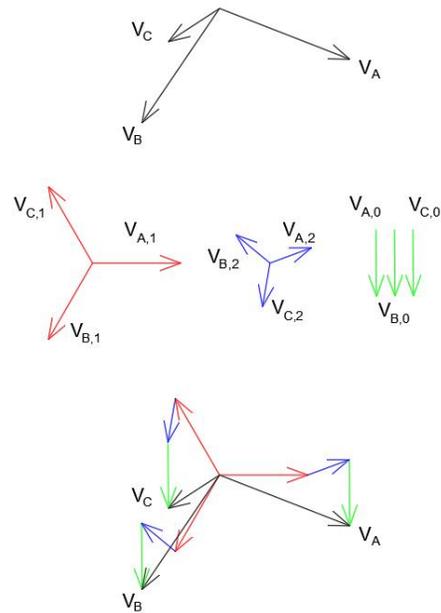
### 3. Refresher on sequence Networks.

### The Purpose of sequence networks

Sequence transform turns unbalanced phasors into balanced phasors:

$$\begin{bmatrix} V_{A,0} \\ V_{A,1} \\ V_{A,2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}$$

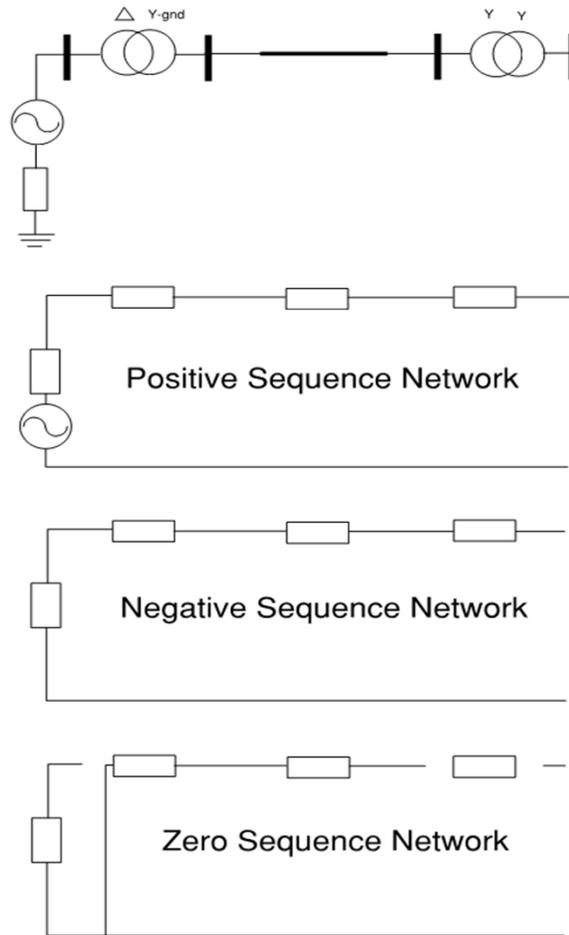
$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_{A,0} \\ V_{A,1} \\ V_{A,2} \end{bmatrix}$$



$$\alpha = e^{\frac{2j\pi}{3}}$$

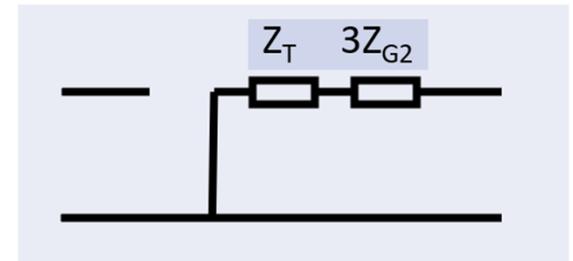
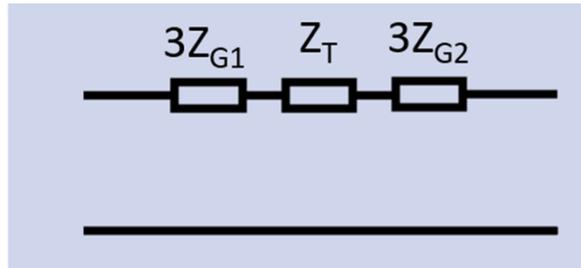
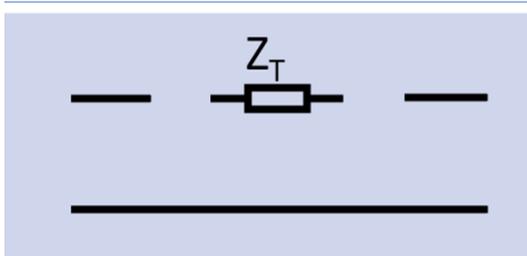
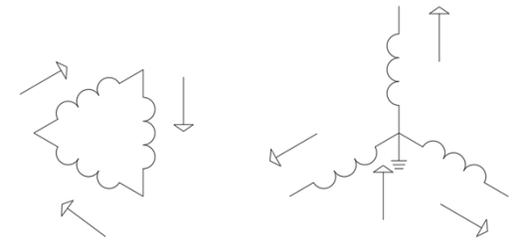
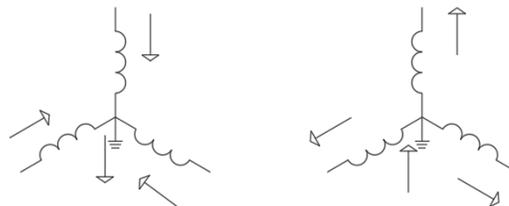
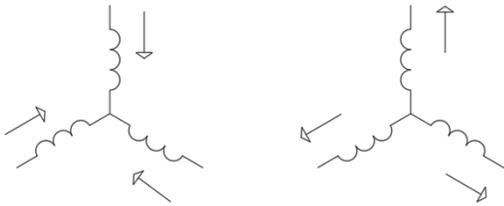
### 3. Refresher on sequence Networks.

### The Purpose of sequence networks



### 3. Refresher on sequence Networks.

### Example transformers



### 3. Refresher on sequence Networks.

## Transformer Connection Table

Transformer	Positive Sequence	Zero Sequence	Transformer	Positive Sequence	Zero Sequence

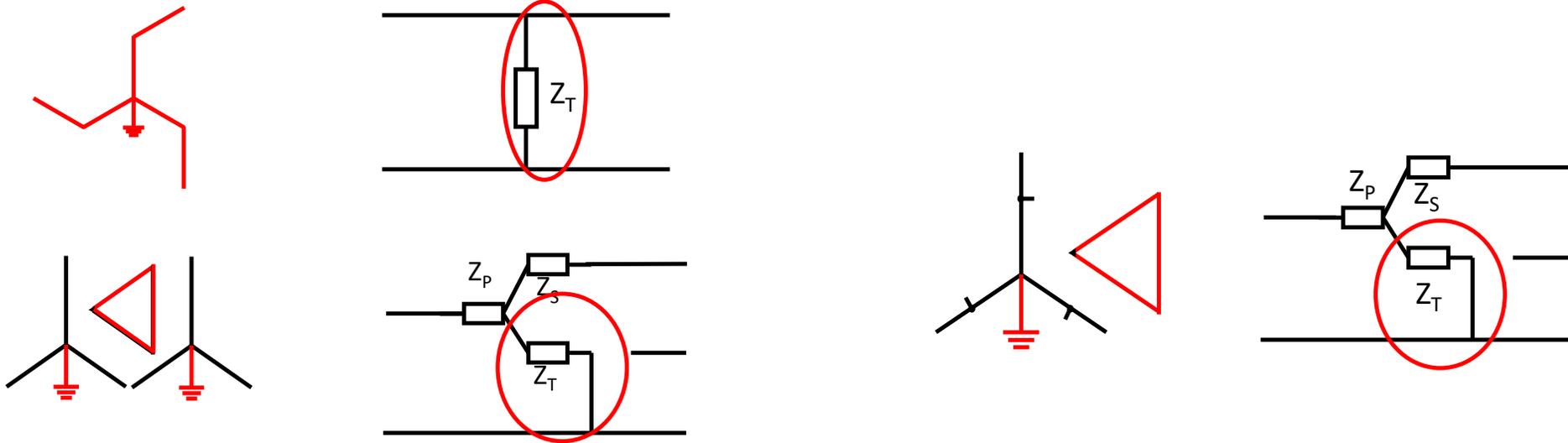
#### 4. So what about “ground source” or “sources of zero sequence currents”?

“Ground Source” or “Zero Sequence Source” are a **misnomer**, or more precisely a **useful simplifying abuse of language**, that has been harmless until now.

To see zero sequence, current the system must be grounded, this **requires connected sources that allow for both negative sequence and zero sequence paths**. The **zero sequence path is provided by transformer** that have the required winding configuration. The **negative sequence path is provided by the rotating generators** on the system.

This has been true until the emergences of Inverter Based Resources (IBR).  
IBR can be programmed to produce

4. So what about “ground source” or “sources of zero sequence currents”? “Ground Source” Transformers



The association of a zig-zig with a ground connection

Or

The association of a Delta connection with another grounded winding connection

Creates the **path for the 3I0 currents**

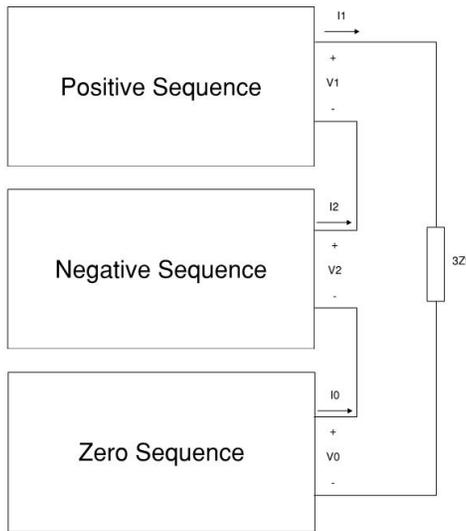
There is actually **no source, only a path**

### 3. Refresher on sequence Networks.

### The Purpose of sequence networks

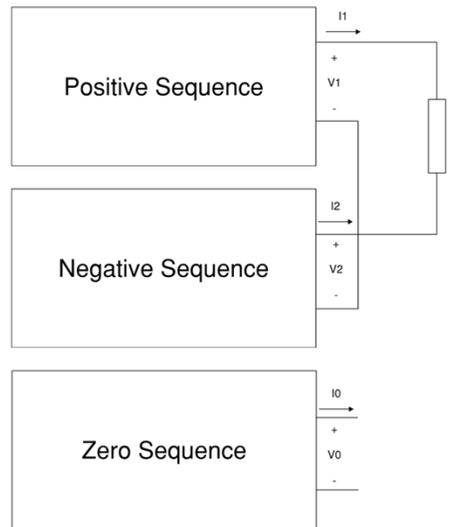
Sequence networks' purpose is to calculate the fault current for asymmetrical faults:

Single Phase to Ground Fault



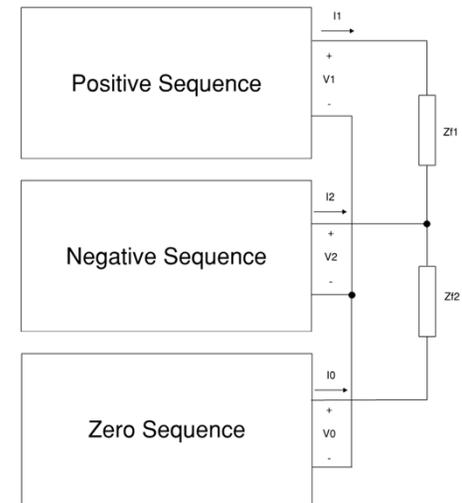
$$\begin{bmatrix} I_{Af,0} \\ I_{Af,1} \\ I_{Af,2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} I_f \\ 0 \\ 0 \end{bmatrix}$$

Phase to Phase Fault



$$\begin{bmatrix} I_{Af,0} \\ I_{Af,1} \\ I_{Af,2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} 0 \\ I_f \\ -I_f \end{bmatrix}$$

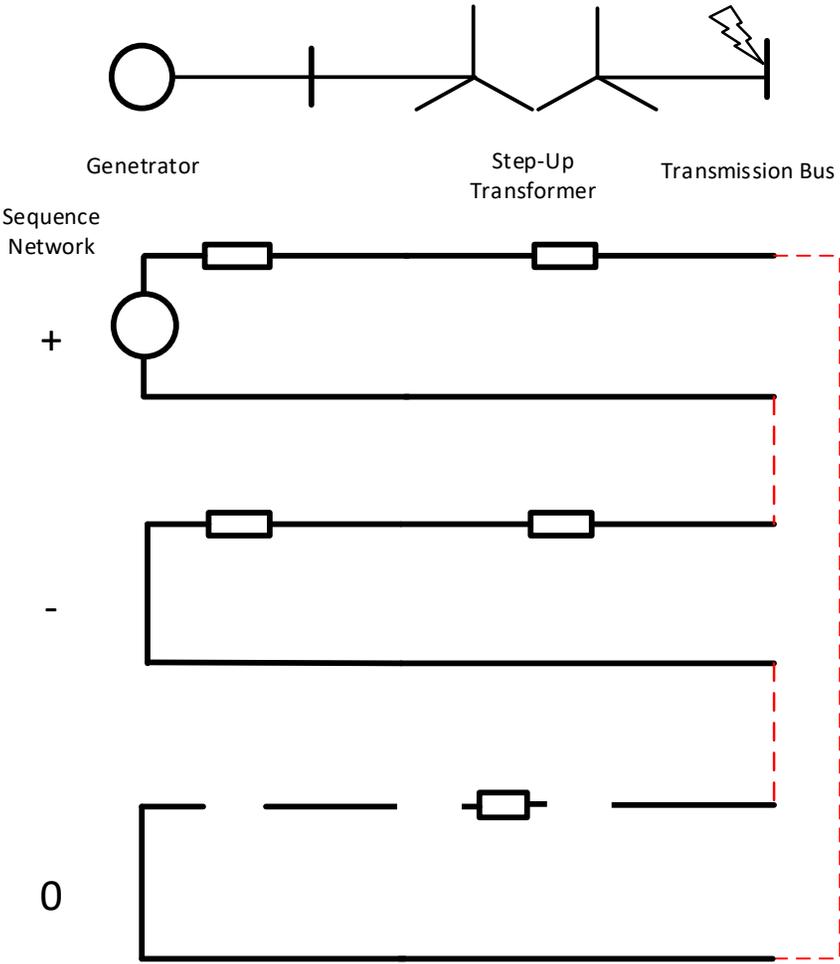
2 Phases to Ground Fault



$$\begin{bmatrix} V_{Af,0} \\ V_{Af,1} \\ V_{Af,2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_{af} \\ 0 \\ 0 \end{bmatrix}$$

5. Example of a grounded system

“Phase to ground” Fault example



## 5. Example of a grounded system

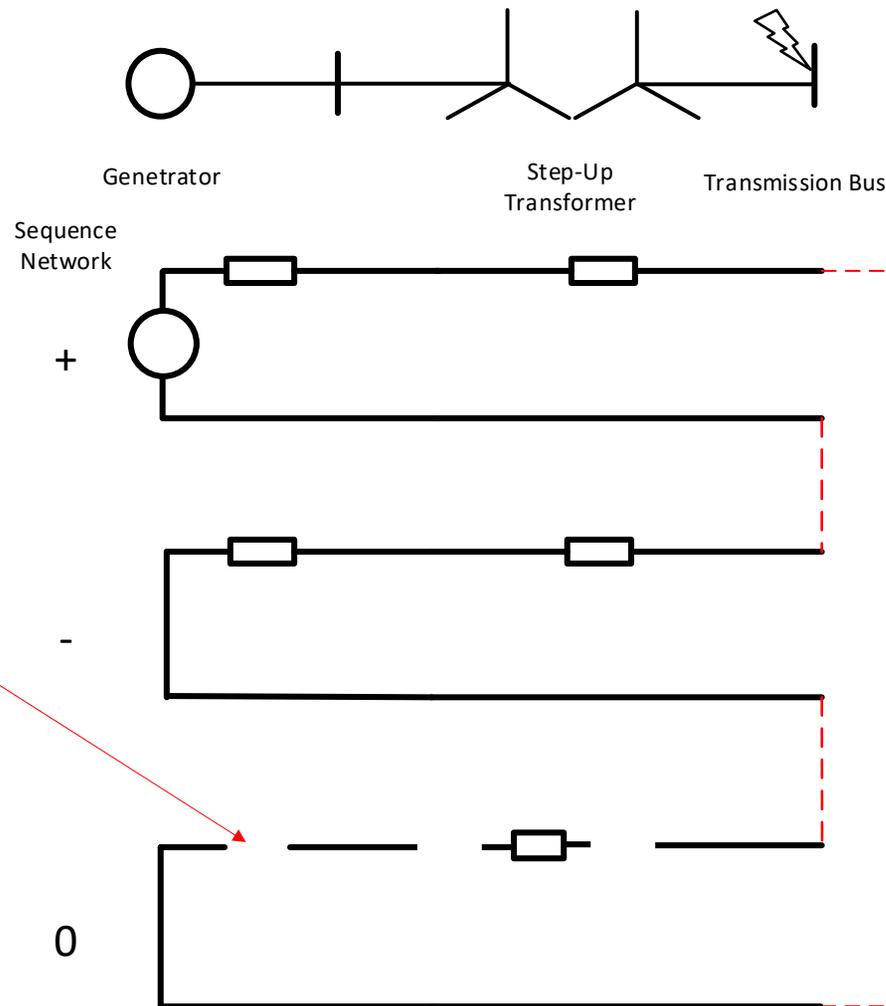
Typical generators are rotating machinery that can easily be damaged by 3I0 currents.

So, by design impedance is added on the neutral connection to ground to reduce these current to a small current.

This makes generator zero sequence practically infinite in most cases.

So, the entire current to the fault is reduced to a small amplitude.

### “Phase to ground” Fault example



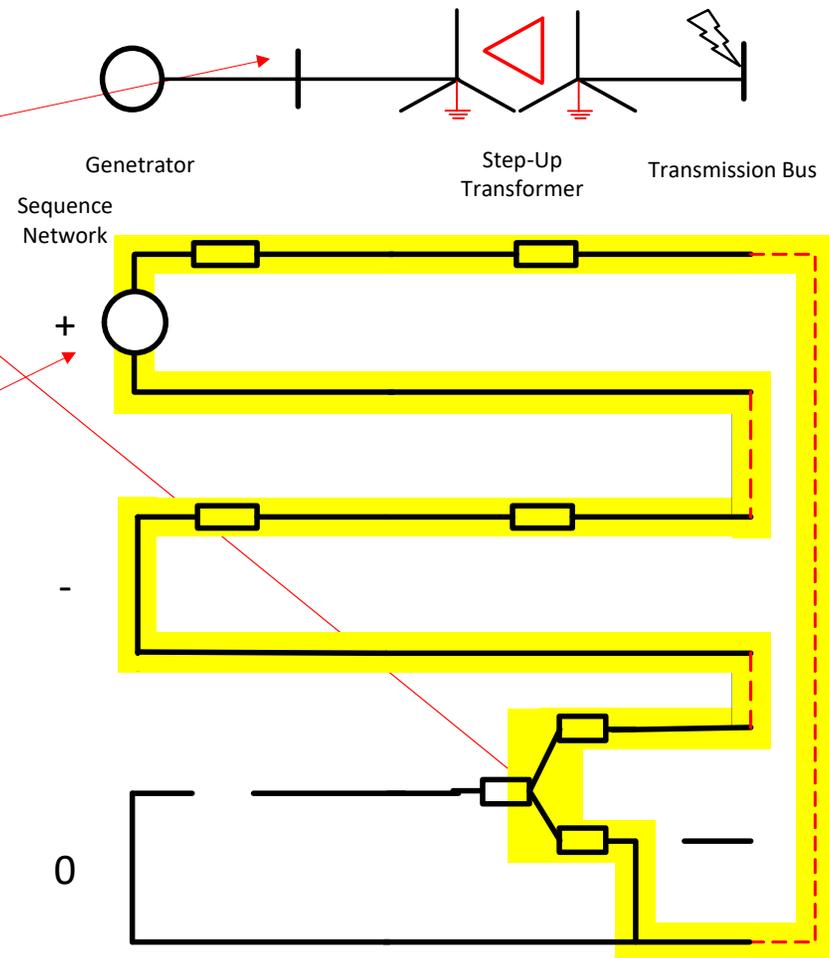
## 5. Example of a grounded system

## “Phase to ground” Fault example

Changing the transformer with a “ground source” transformer closes the path.

The fault current will be large...

But the **only source is still only located on the positive sequence network.**

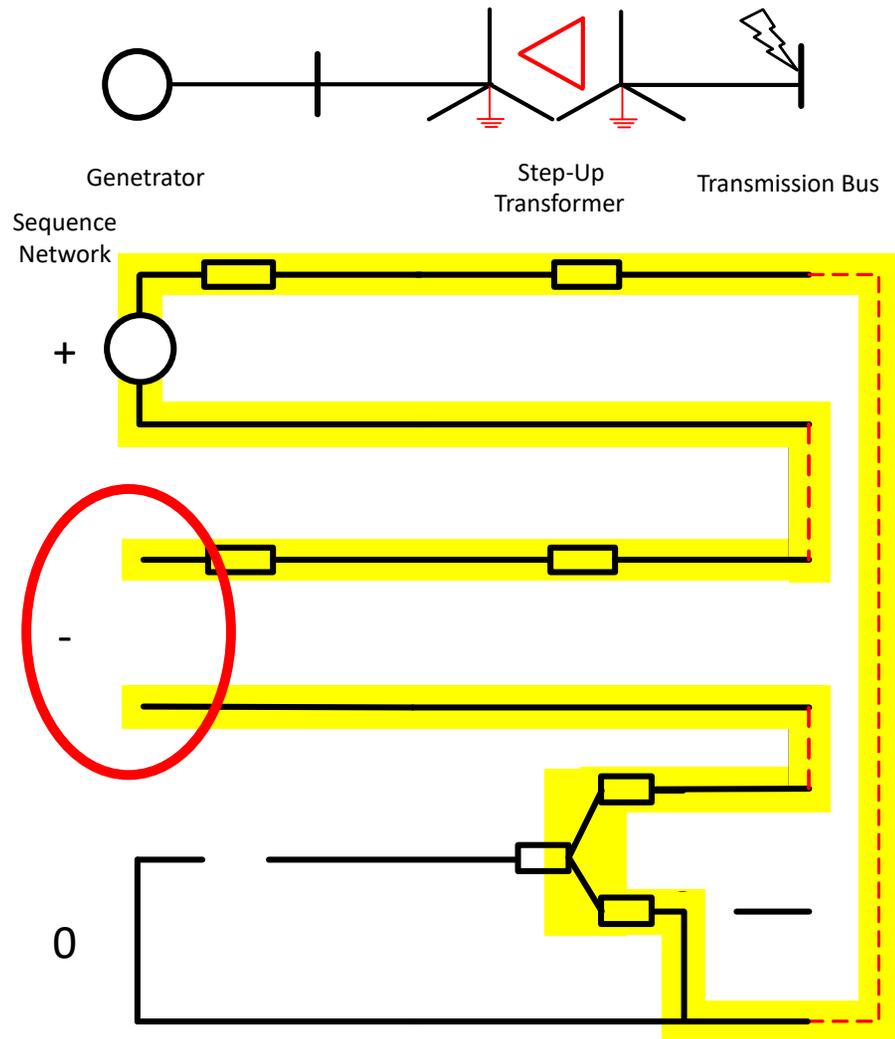


## 6. Example of a IBR connected to a ground system.

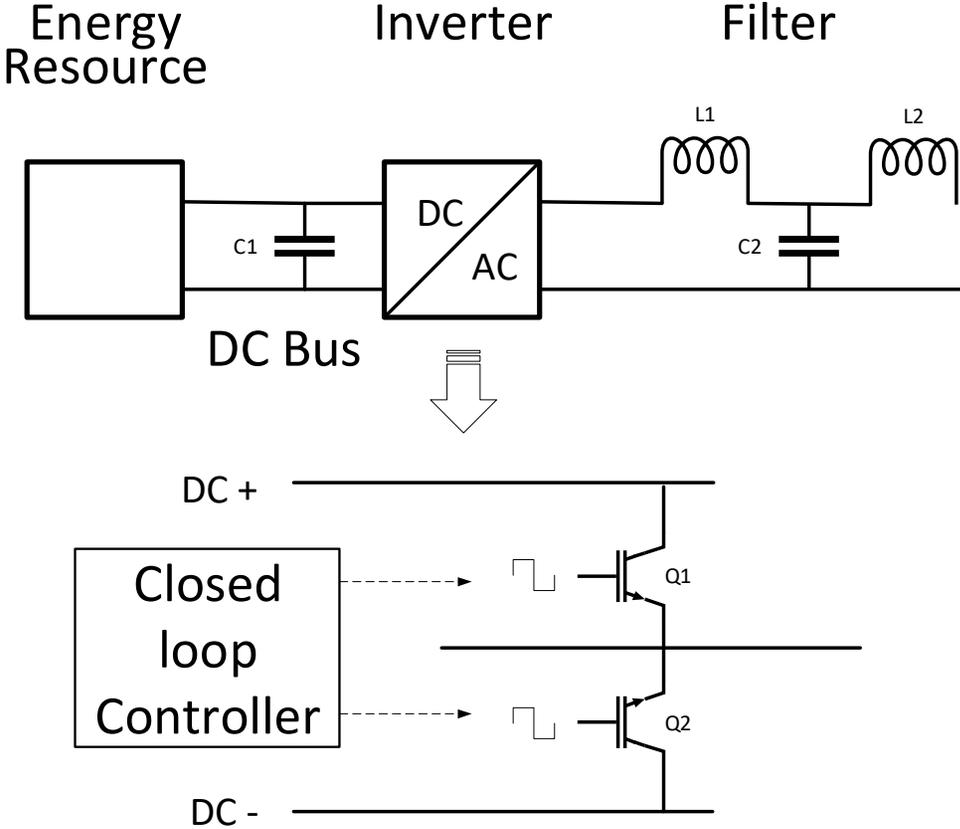
Typical Inverter Base Resources are built to only positive sequence current.

The equivalent negative and positive sequence network is open.

If a “ground source” transformer was used, then there is still an open part of the circuit on the negative sequence network.



6. Example of a IBR connected to a ground system.



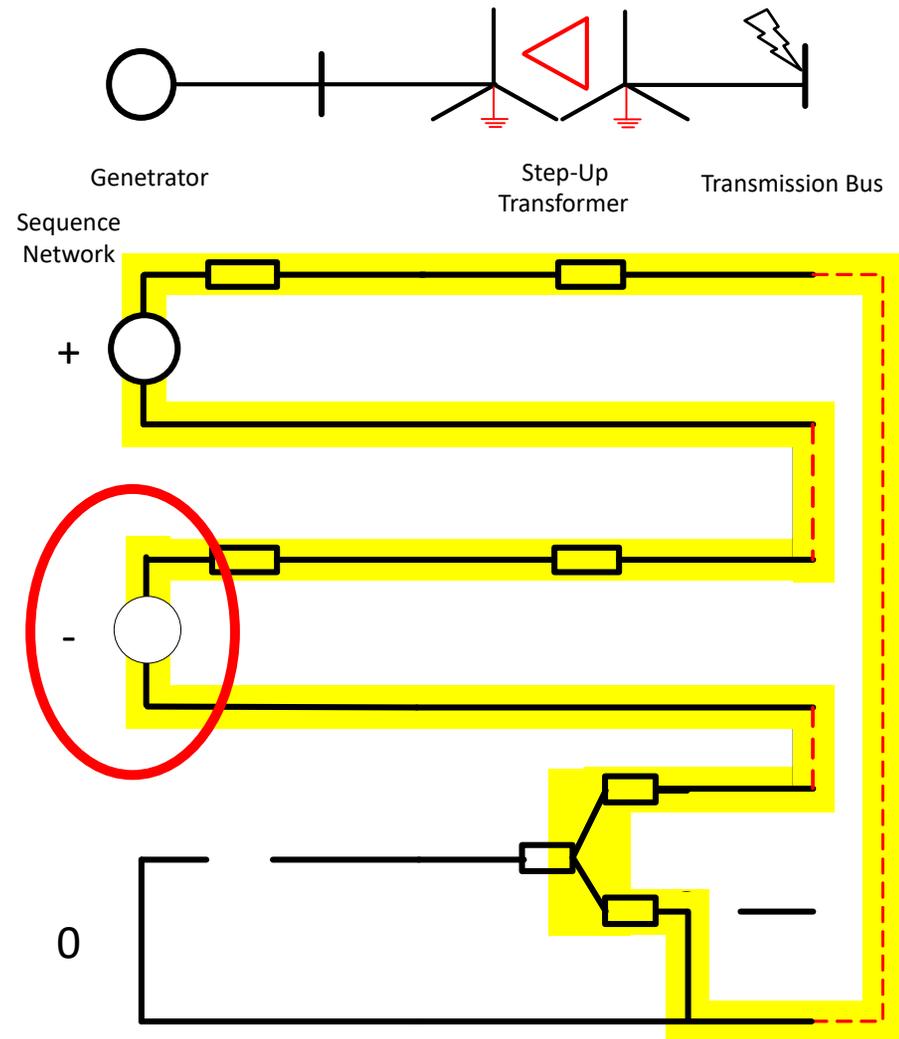
## 6. Example of a IBR connected to a ground system.

Inverters can be programmed to be sources on the negative and zero sequence network.

Since a ground transformer typically provide the closed path on transmission systems, only the negative sequence source the necessary to allow currents to flow.

If the IBR is the only source feeding the fault, then the source will need to be of equal magnitude and angle.

Since most of the system impedance is reactive, the angle in reference to the voltages will be close to 90 degrees.



## 6. Example of a IBR connected to a ground system.

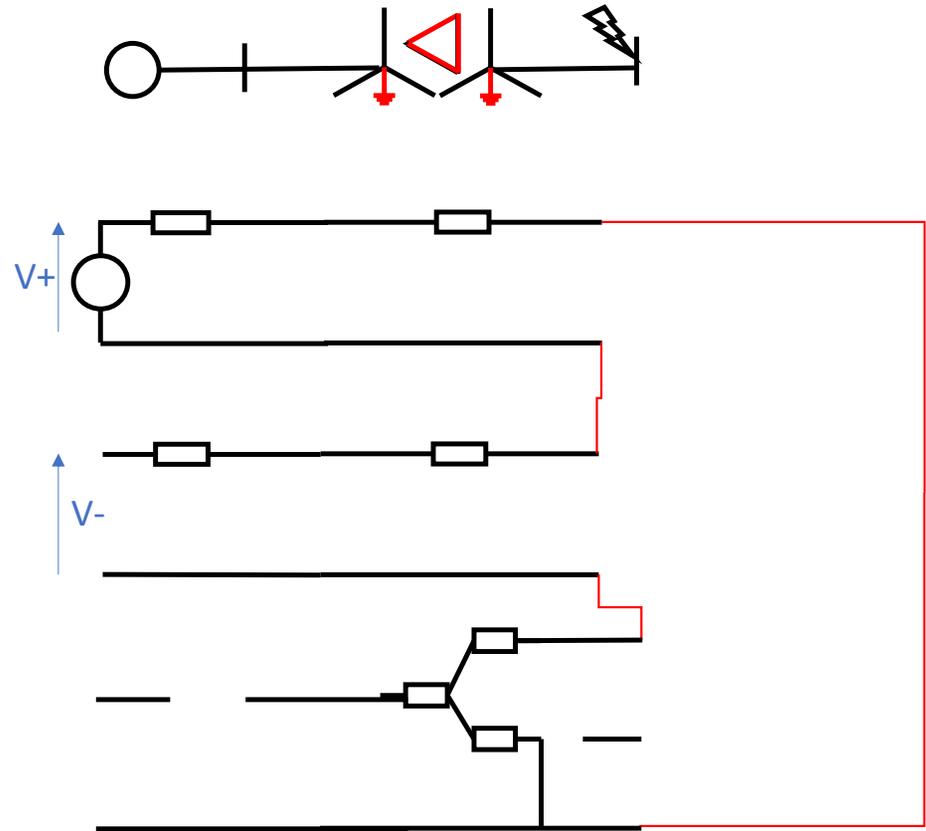
When a phase to ground fault start the source voltage theoretically will appear as the negative sequence voltage at the generator terminal. That is because no fault current is flowing.

$$I_+ = I_- = I_0 = 0$$

and

$$V_+ = -V_-$$

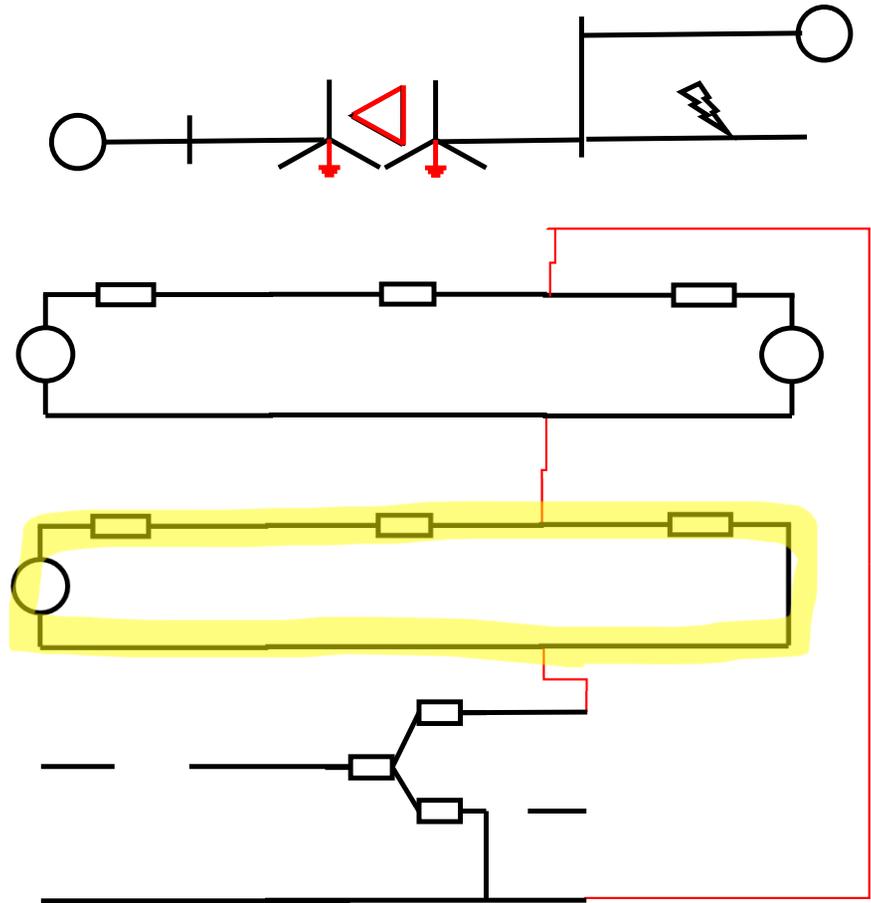
at the start of the fault



## 6. Example of a IBR connected to a ground system.

While connected to the grid, the mix of generation offers a path for negative sequence current produced by the IBR. This means that the IBR can “push” the negative sequence at any angle. That is because the equivalent system generators will close the path of the negative sequence network.

If the **angle is not reactive (or close)**, the directional elements of protective relays will mis-operate. **Refer to Sandia Report.**



## 7. What could become problematic if the IBR do not allow for negative sequence.

Medium and low voltage equipment are often used in small geographic network where it is easy to survey to find an insulation failure. Where the source impedance is small (fault energy is large), creating an **ungrounded system** is preferred as it **reduces the likelihood of damage**.

This means that these equipment are likely to be submitted to **larger voltages** due to the large zero sequence voltage under ground fault conditions.

For this reason, **IEEE recommends that equipment below 100kV be capable of withstanding proportionally larger voltage** in reference to its rated voltages. Similarly switching ungrounded sources is only tested on breaker rated below 100kV.

If IBR are not programmed to produce negative sequence, progressively the transmission system will become ungrounded. The operation will be taken in a mode that it was not designed for.

This will likely lead to accelerated equipment aging and failure on the entire transmission system.

## 7. What could become problematic if the IBR do not allow for negative sequence.

Distribution system will see a similar problem as the typical end customers equipment (PCs, TV, appliances,...) are not designed to withstand more than 20% overvoltage for only a very short time. (less than a cycle).

An ungrounded system would produce a **73% rise on the un-faulted phases**. These equipment's will also experience accelerated failure.

A survey of equipment cost shows that Increasing the insulation and voltage operation capability increases the cost of the equipment by 15%.

Total US Transmission assets is estimated at \$1.5T. It is estimated that to rebuild from the ground up the cost is \$5T.

If the transmission system became ungrounded, we can deduce that the cost impact would be of the order **of 15% of \$5T= \$750B**

**It seems the cost of designing Inverters that produce adequate output of negative sequence should be far less.**

**7. What could become problematic if the IBR do not allow for negative sequence or do not allow for enough of it, or do not control it adequately.**

Because no current will be produced, we will no longer be able to locate the fault, on the transmission as well as the distribution systems. The system insulation and voltage breaking capability will need to be raised.

Though it will be decades until a 100% IBR system would exist, it is very likely that in the **near future islands on 100% IBRs will be created.**

For this reason, the negative sequence source problem **must be addressed TODAY.**

# 8. Model Simulations



**Generator Data**

Generators at GeneratorBus 29.kV

Unit '1': On-Line

Buttons: Edit, On/Off-Line, New, Delete

Internal V-Source: p.u. = 1.0, Ref. angle = 0.0

Current Limits (A): A: 0, B: 0

Power Flow Regulation:  Regulates voltage,  Fixed P+Q output

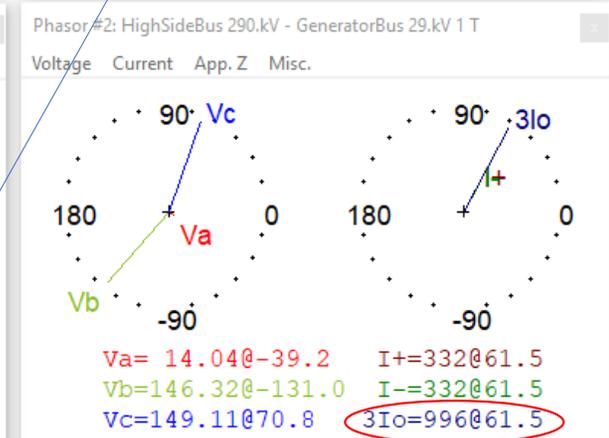
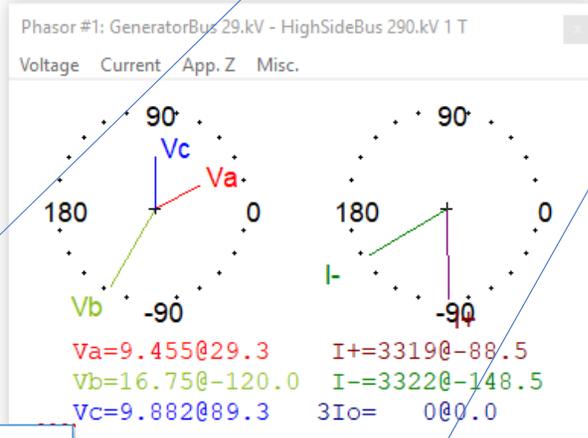
Hold V = 1.0 pu

At: GeneratorBus 29.kV 0 (PV)

Tags: None

Buttons: Done, Help

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**Generating Unit Info**

ID = 1, Unit rating = 100 MVA

Impedances (pu based on unit MVA):

- Subtransient: 0.2
- Transient: 0.3 (circled in red)
- Synchronous: 3.0 (circled in red)
- sequence: 0.2
- o sequence: 9999

Neutral Impedance (in actual Ohms): 0

Scheduled generation: MW = 0, MVAR = 0

P and Q limits (MW and MVAR): Pmax = 9999, Pmin = -9999, Qmax = 9999, Qmin = -9999

Date In-service: N/A, Out-of-service: N/A

Tags: None

Buttons: OK, Cancel, Help

**2-Winding Transformer Data**

HighSideBus 290.kV - GeneratorBus 29.kV

Name = Line, Ckt ID = 1, MVA1 = 0, MVA2 = 0, MVA3 = 0

MVA base for per-unit quantities = 100

Parameters: R = 0.002, X = 0.05, B = 0, Ro = 0.002, Xo = 0.05, Bo = 0

Neutral grounding Z (ohms): Zg1 = 0

HighSideBus 290.kV: Tap kV = 290, G1 = 0, B1 = 0, G10 = 0, B10 = 0

GeneratorBus 29.kV: Tap kV = 29, G2 = 0, B2 = 0, G20 = 0, B20 = 0

Metered at: HighSideBus 290.kV

**Transmission Line Data**

HighSideBus 290.kV - EndOfLine 290.kV

Name = Line, Ckt ID = 1

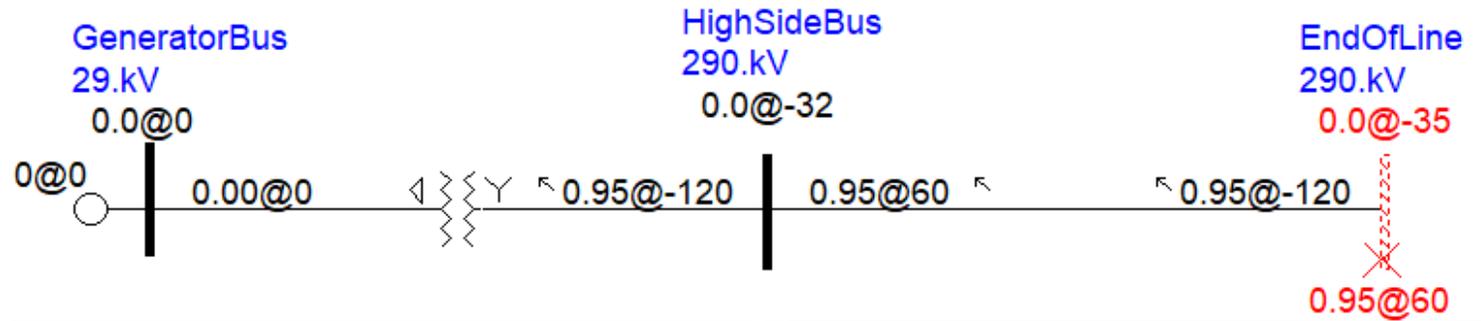
Length = 10 mi, Type = Delta Dove

Branch Parameters: R = 0.00198, X = 0.00716, R0 = 0.0053, X0 = 0.03508

Current Ratings (A): A: 100, B: 200, C: 300, D: 400

**Note for future comparison that the Angle of the 3Io is 61 degrees**

## 8. Model Simulations



Generating Unit Info

ID=  Unit rating=  MVA

Impedances (pu based on unit MVA)

Subtransient	<input type="text" value="0."/>	+j	<input type="text" value="0.2"/>	<input type="button" value="Fill"/>
Transient	<input type="text" value="0."/>	+j	<input type="text" value="0.3"/>	
Synchronous	<input type="text" value="0."/>	+j	<input type="text" value="3."/>	
- sequence	<input type="text" value="0."/>	+j	<input type="text" value="9999."/>	
o sequence	<input type="text" value="0."/>	+j	<input type="text" value="9999."/>	

Neutral Impedance (in actual Ohms)

Scheduled generation. Enter MVAR for PQ buses only

MW=

MVAR=

P and Q limits (MW and MVAR)

Pmax=

Qmax=

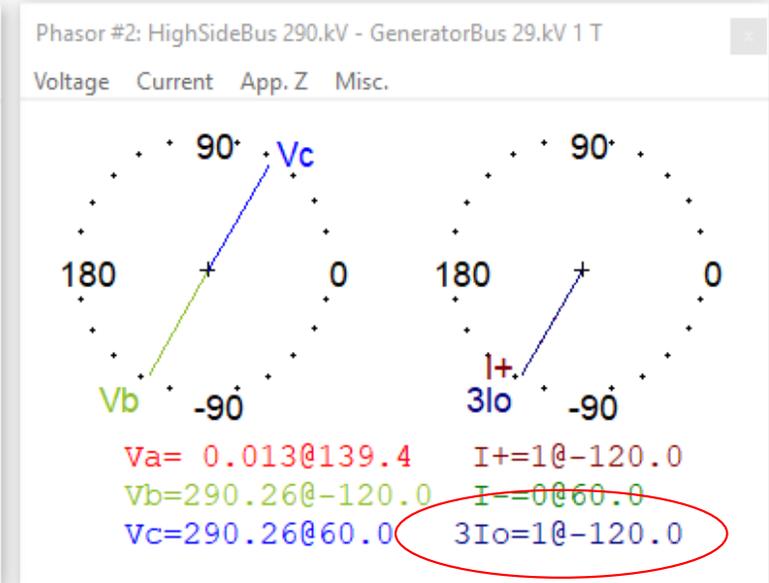
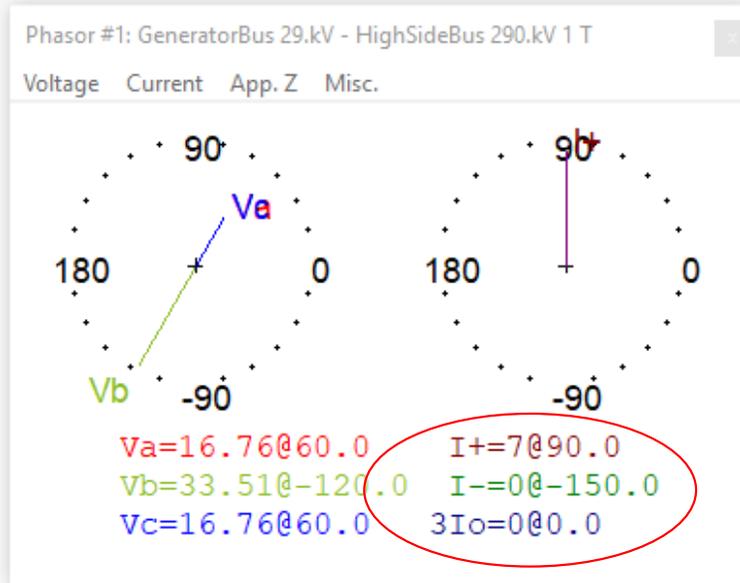
Pmin=

Qmin=

Date In-service:

Out-of-service:

Tags:



## 8. Model Simulations

The system shunt capacitance can provide the negative sequence path

Transmission Line Data

HighSideBus 290.kV - EndOfLine 290.kV

Name= Line Ckt ID= 1

Length= 100. mi Type Delta Dove

Branch Parameters

R= 0.01977 X= 0.07162 Recompute from table

R0= 0.05297 X0= 0.35077

G1= 0. B1= 0.29844 G2= 0. B2= 0.29844

G10= 0. B10= 0.11234 G20= 0. B20= 0.11234

Current Ratings (A)

A: 100. B: 200. C: 300. D: 400.

I^2T Rating = 0. Amp^2 Sec

Metered at: HighSideBus 290. kV

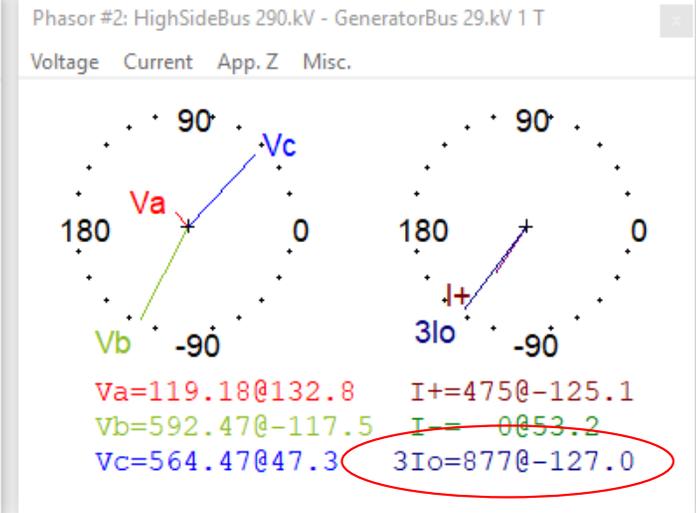
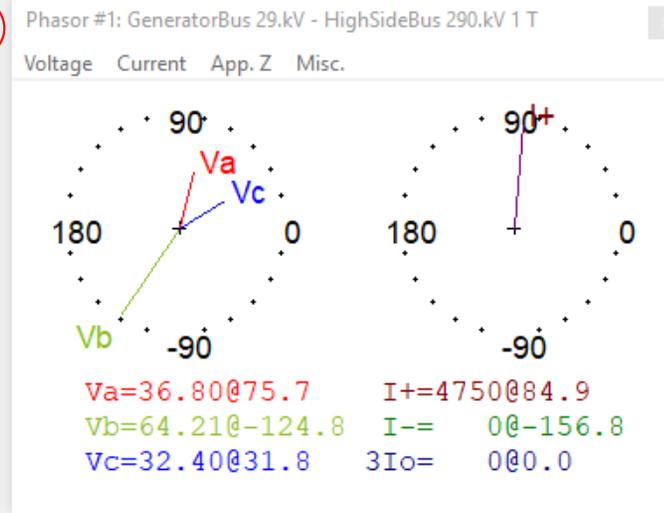
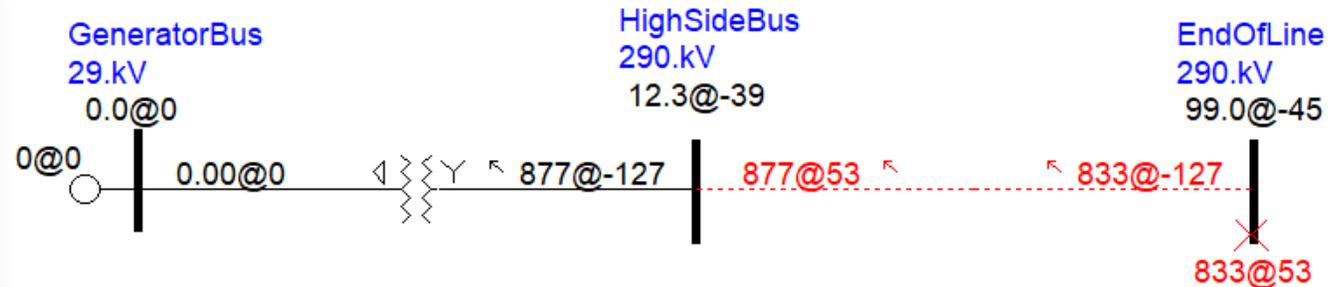
Memo:

Date In-service: N/A Out-of-service: N/A

Tags: None

Mutuals... OK Cancel Help

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## 8. Model Simulations

It acts similarly to shunt capacitor bank

**Transmission Line Data**

HighSideBus 290.kV - EndOfLine 290.kV  
 Name= Line Ckt ID= 1  
 Length= 100. mi Type Delta Dove

**Branch Parameters**

R= 0.01977 X= 0.07162  
 R0= 0.05297 X0= 0.35077 Recompute from table

G1= 0. B1= 0. G2= 0. B2= 0.  
 G10= 0. B10= 0. G20= 0. B20= 0.

**Current Ratings (A)**

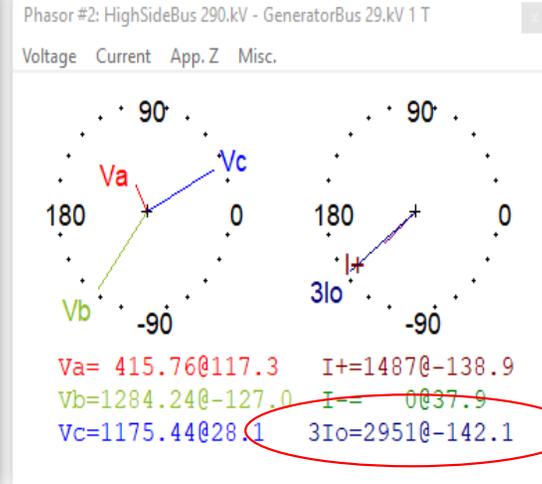
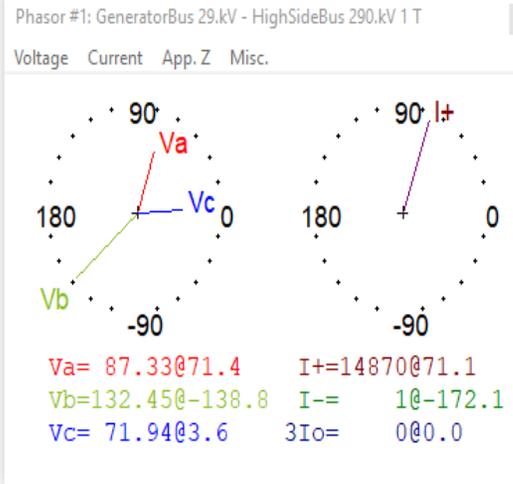
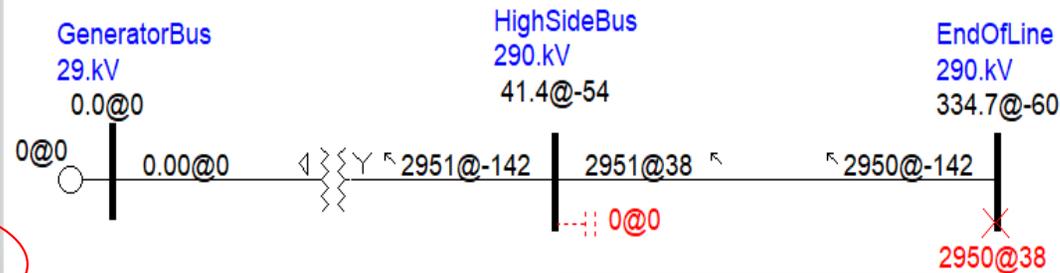
A: 100. B: 200. C: 300. D: 400.  
 I^2T Rating= 0. Amp^2 Sec

Metered at: HighSideBus 290. kV

Date In-service: N/A Out-of-service: N/A  
 Tags: None

OK Cancel Help

Last changed Aug 12, 2019



**Shunt Data**

Shunt Unit Data

ID= 1

Admittances (B>0 for capacitor)

G= 0. B= 0.9 Convert

G0= 0. B0= 0.

3-winding transformer shunt

Date in-service: N/A Out-of-service: N/A  
 Tags: None

OK Cancel Help

**Convert Shunt Power to Admittance**

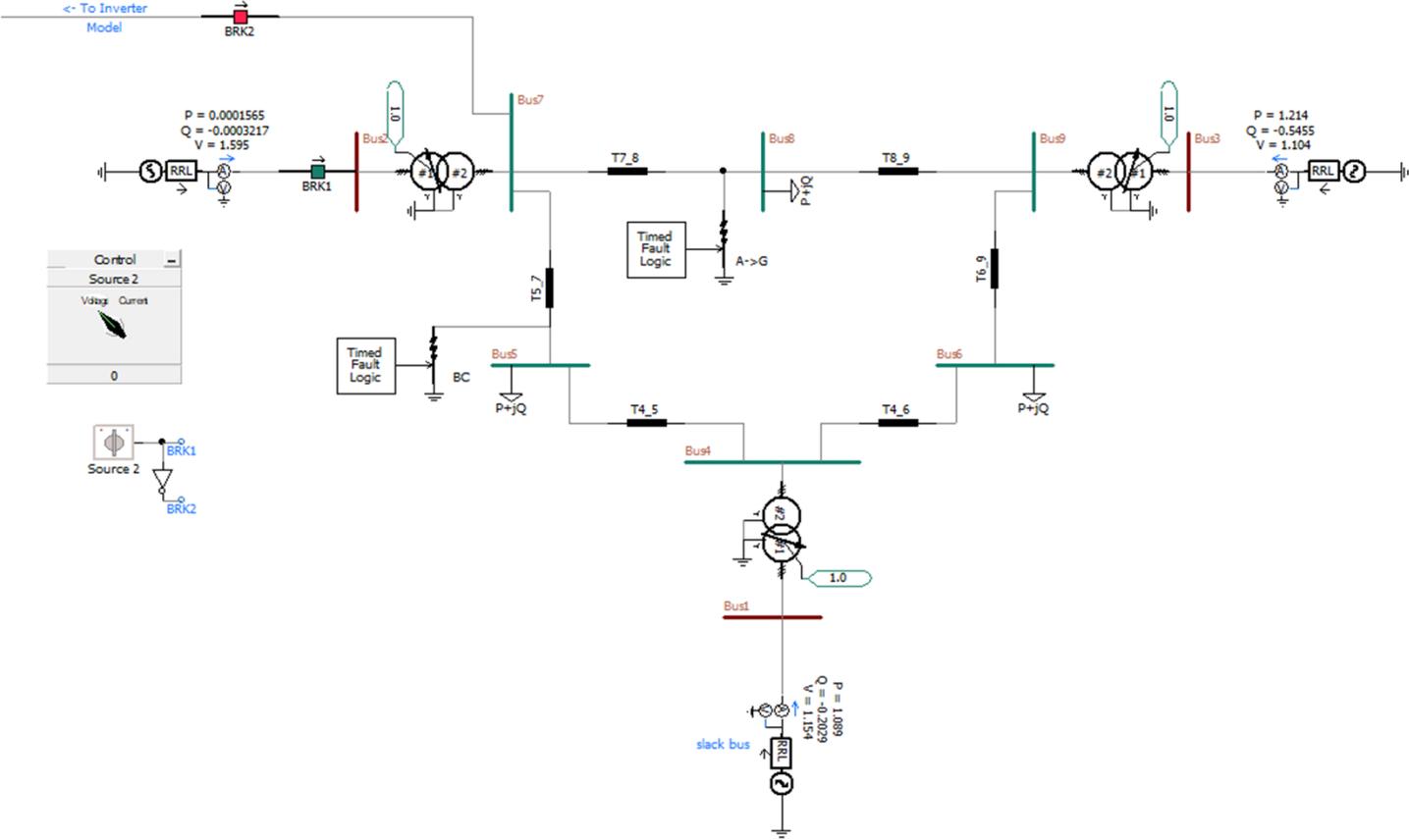
Power at 1.0 pu voltage

MW= 0. MVAR= -90. Convert

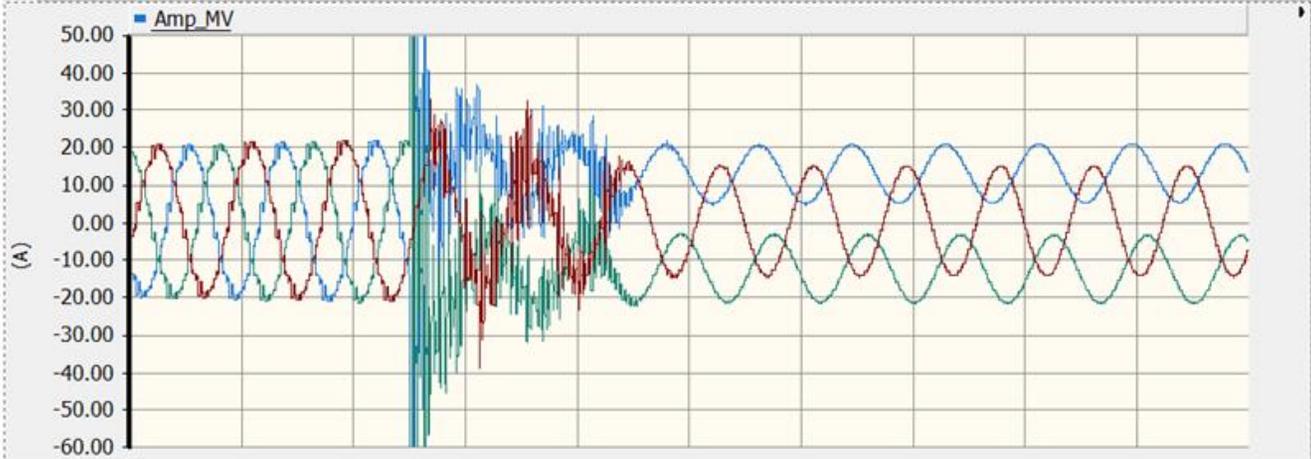
MVAR>0 for reactor; <0 for capacitor

Convert Cancel Help

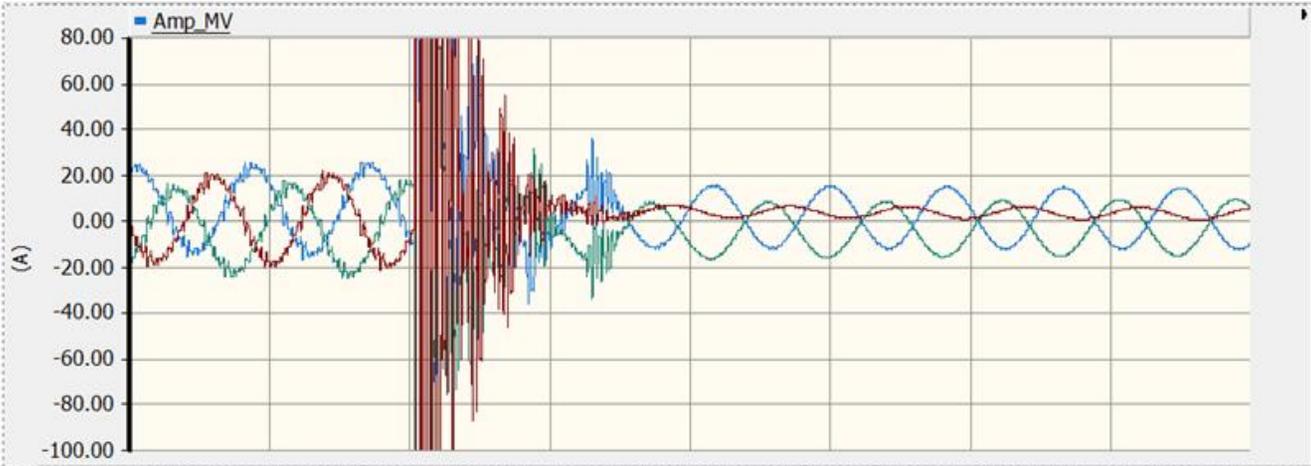
# PSCAD Simulation



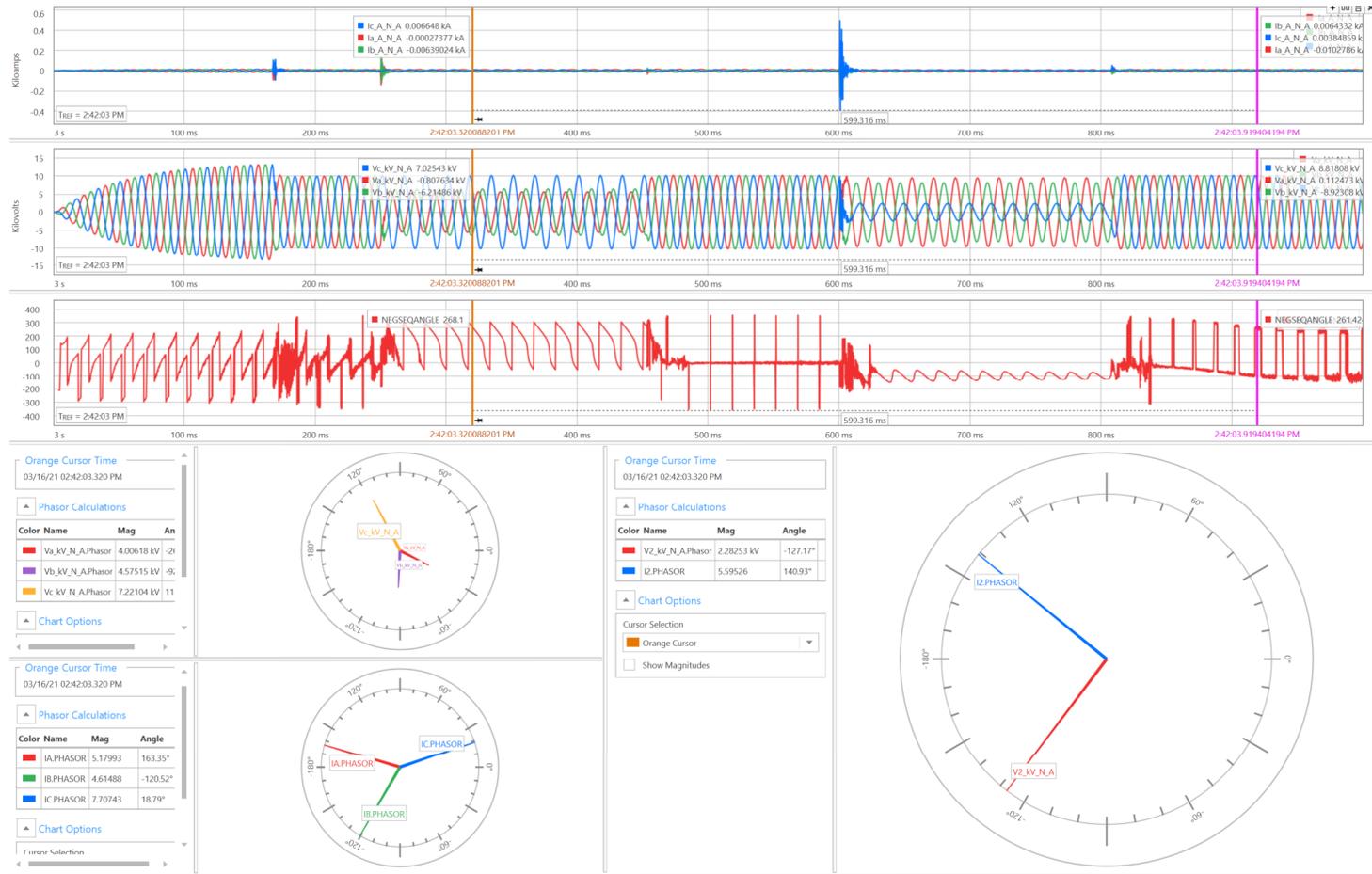
# Inverter Output During Line-to-Ground Fault



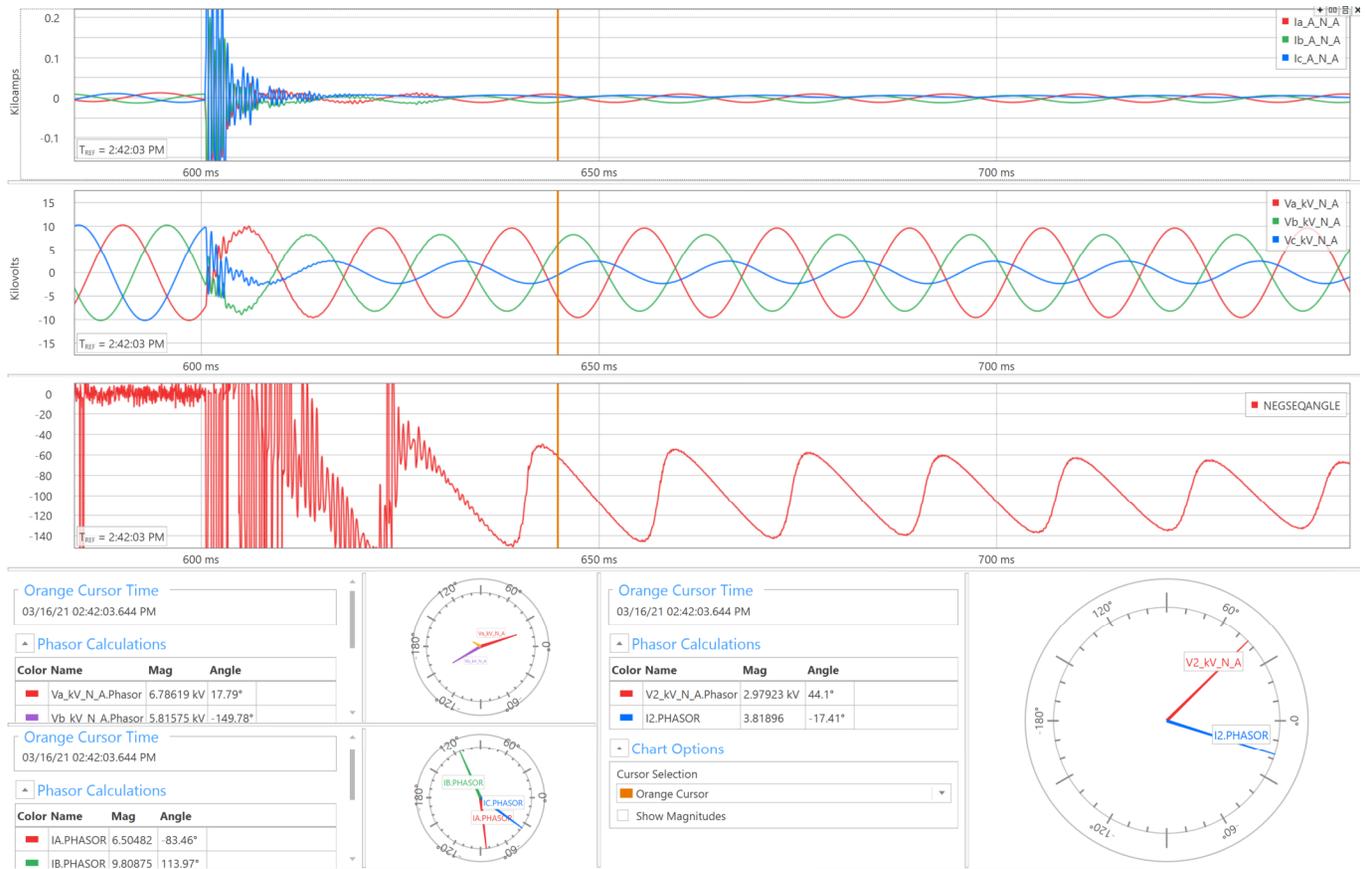
# Inverter Output During Line-to-Line Fault



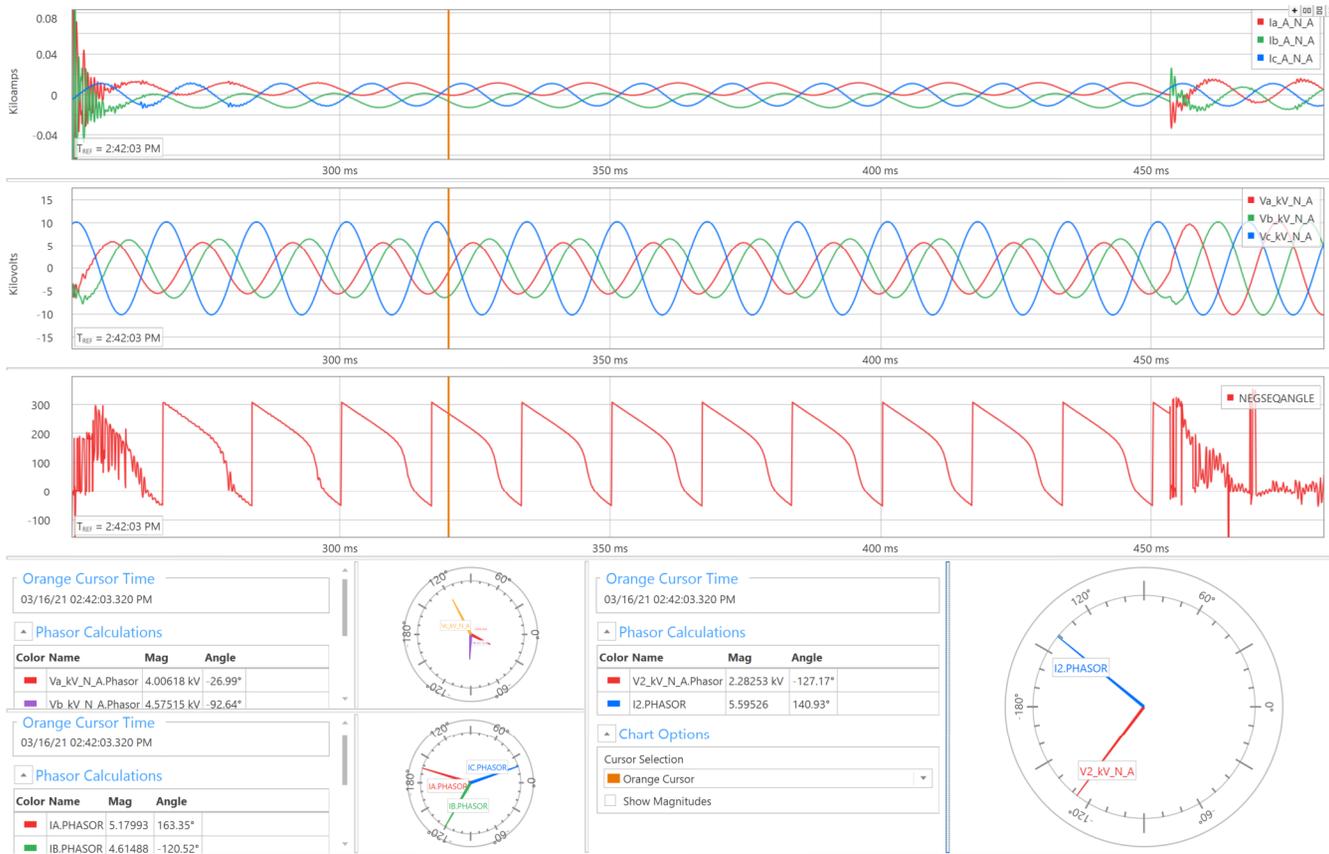
# Inverter Output During L-g & L-L Faults



# Inverter Output During L-L Fault



# Inverter Output During L-g Faults



## Conclusion

1. The grid needs to remain grounded
2. Inverter based resources could pose a challenge to grounding
3. There is still some work to do in the inverters to ensure system grounding
4. When a portion of the grid has high IBR penetration, it is important to study this in a transient modeling software

Questions ?