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).

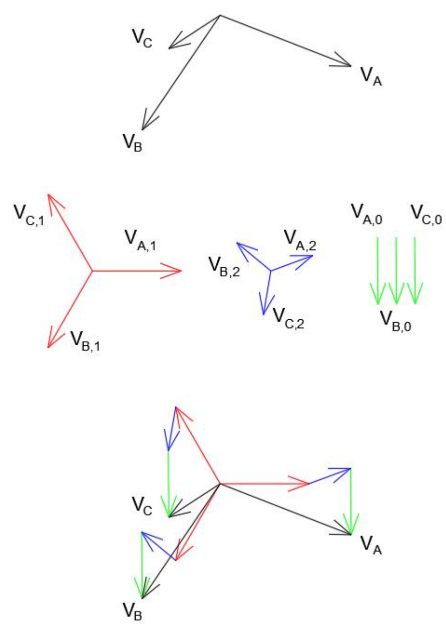
3. Refresher on sequence Networks.

The Purpose of sequence networks

Sequence transform turns unbalanced phasors into balanced phasors:

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

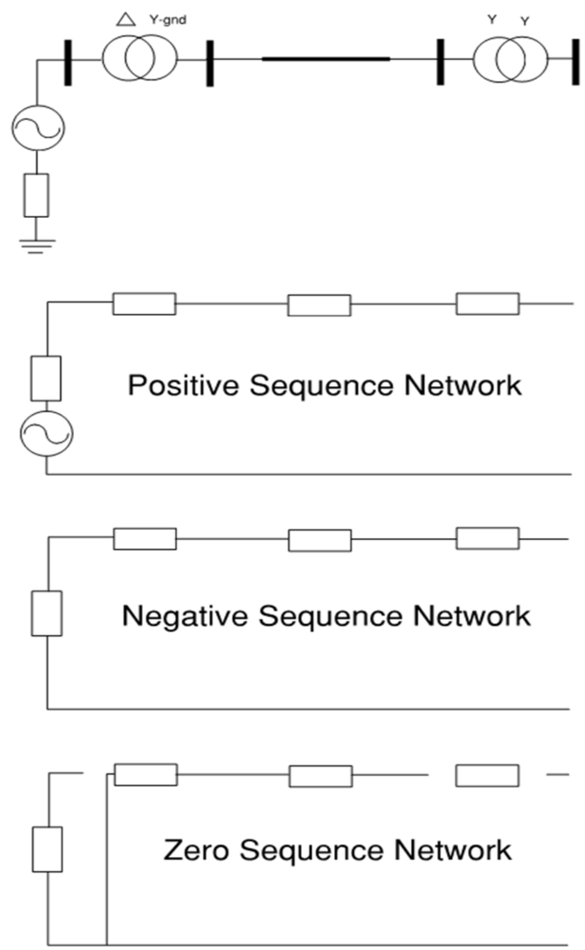
$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}\begin{bmatrix} V_{A,0} \\ V_{A,1} \\ V_{A,2} \end{bmatrix}$$



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

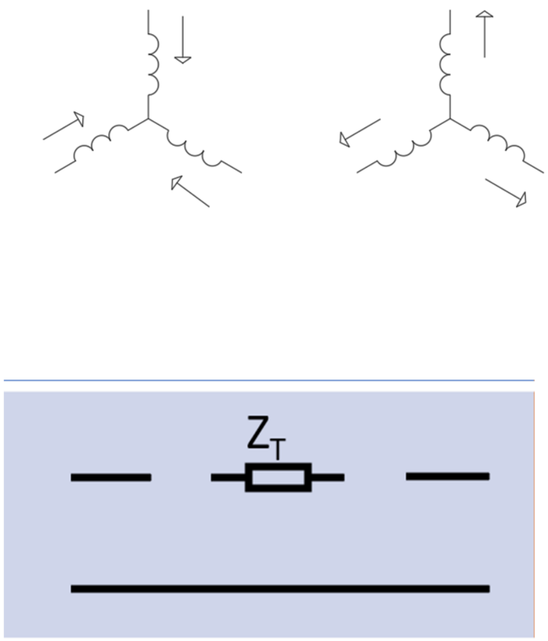
3. Refresher on sequence Networks.

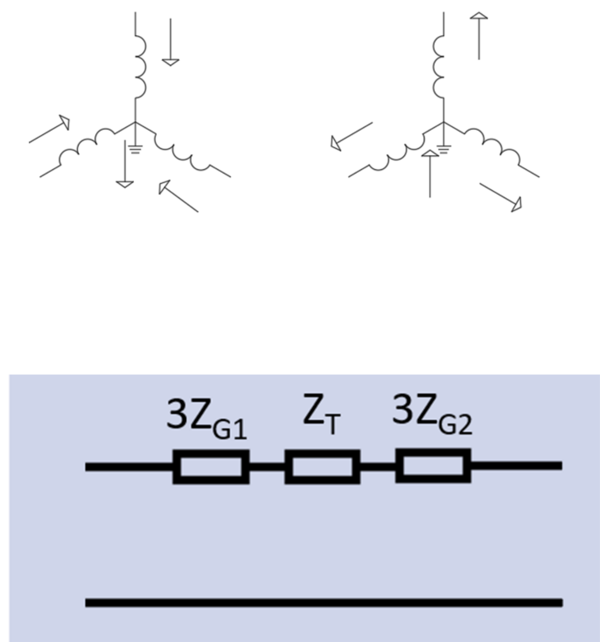
The Purpose of sequence networks

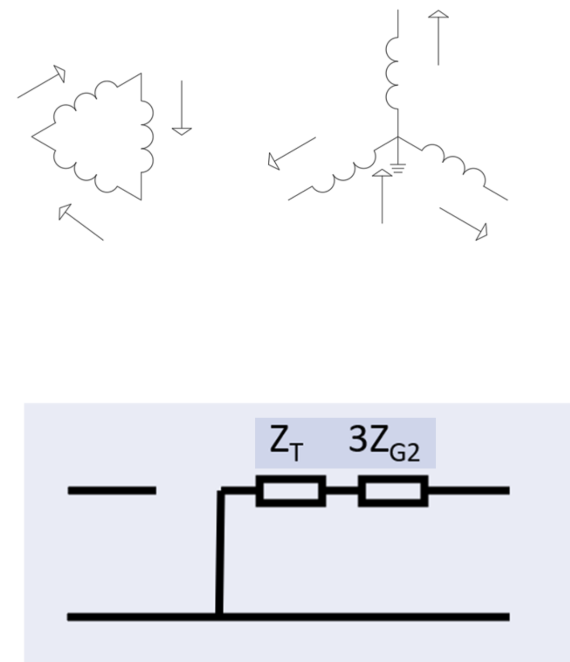


3. Refresher on sequence Networks.

Example transformers

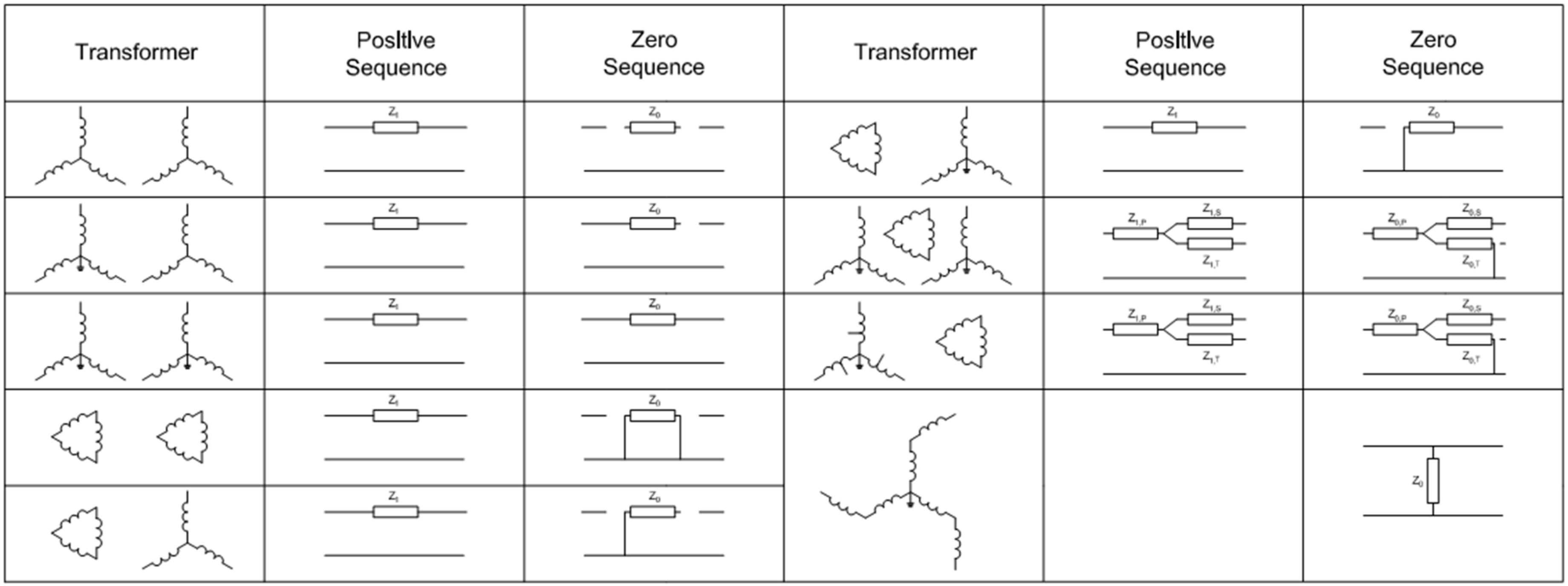






3. Refresher on sequence Networks.

Transformer Connection Table



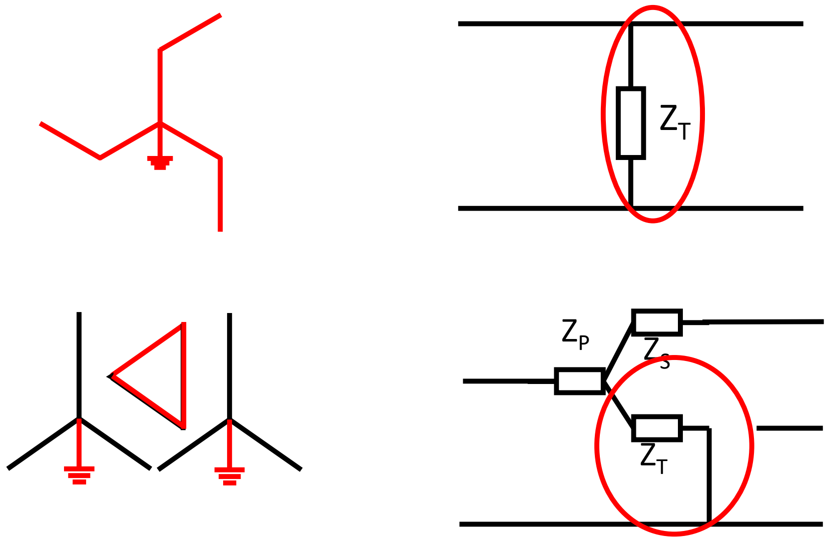
4. So what about “ground source” or “sources of zero sequence currents”?

“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.

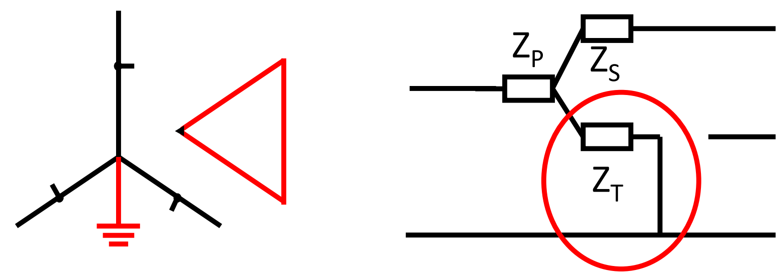
This has been true until the emergences of Inverter Based Resources (IBR).
IBR can be programmed to produce

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**



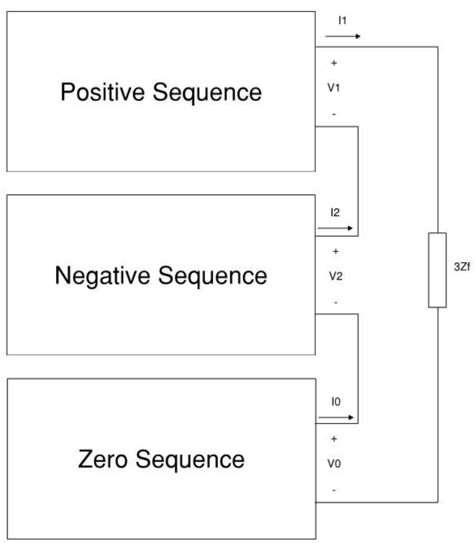
There is actually **no source, only a path**

3. Refresher on sequence Networks.

The Purpose of sequence networks

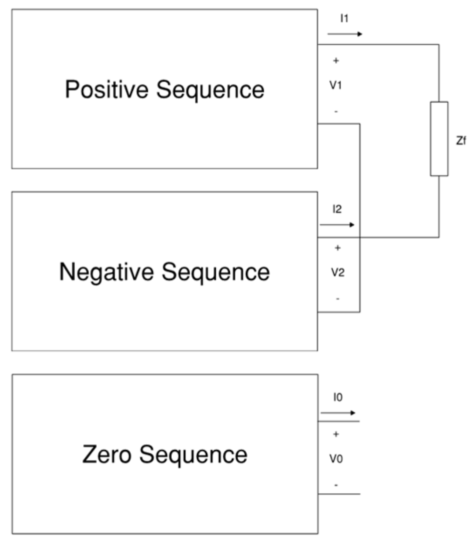
Sequence networks' purpose is to calculate the fault current for asymmetrical faults:

Single Phase to Ground Fault



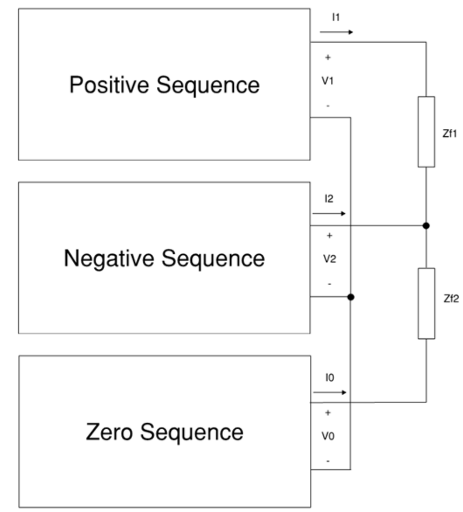
$$\begin{bmatrix} I_{Af,0} \\ I_{Af,1} \\ I_{Af,2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_f \\ 0 \\ 0 \end{bmatrix}$$

Phase to Phase Fault



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

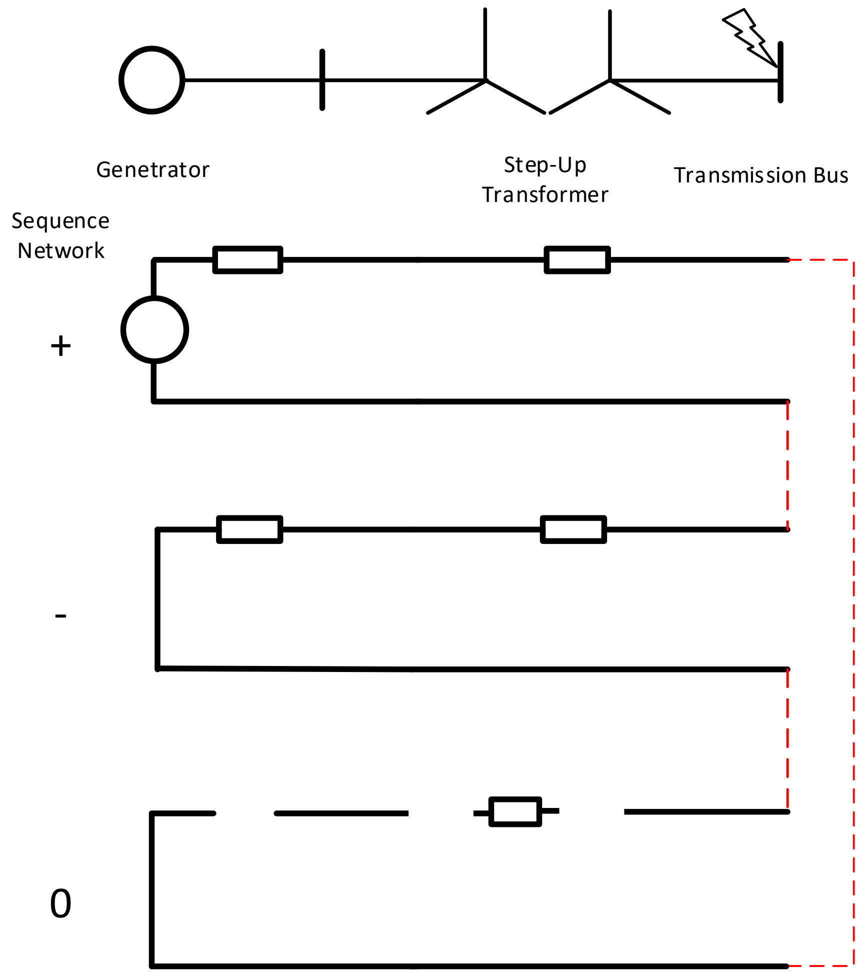
2 Phases to Ground Fault



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

5. Example of a grounded system

“Phase to ground” Fault example

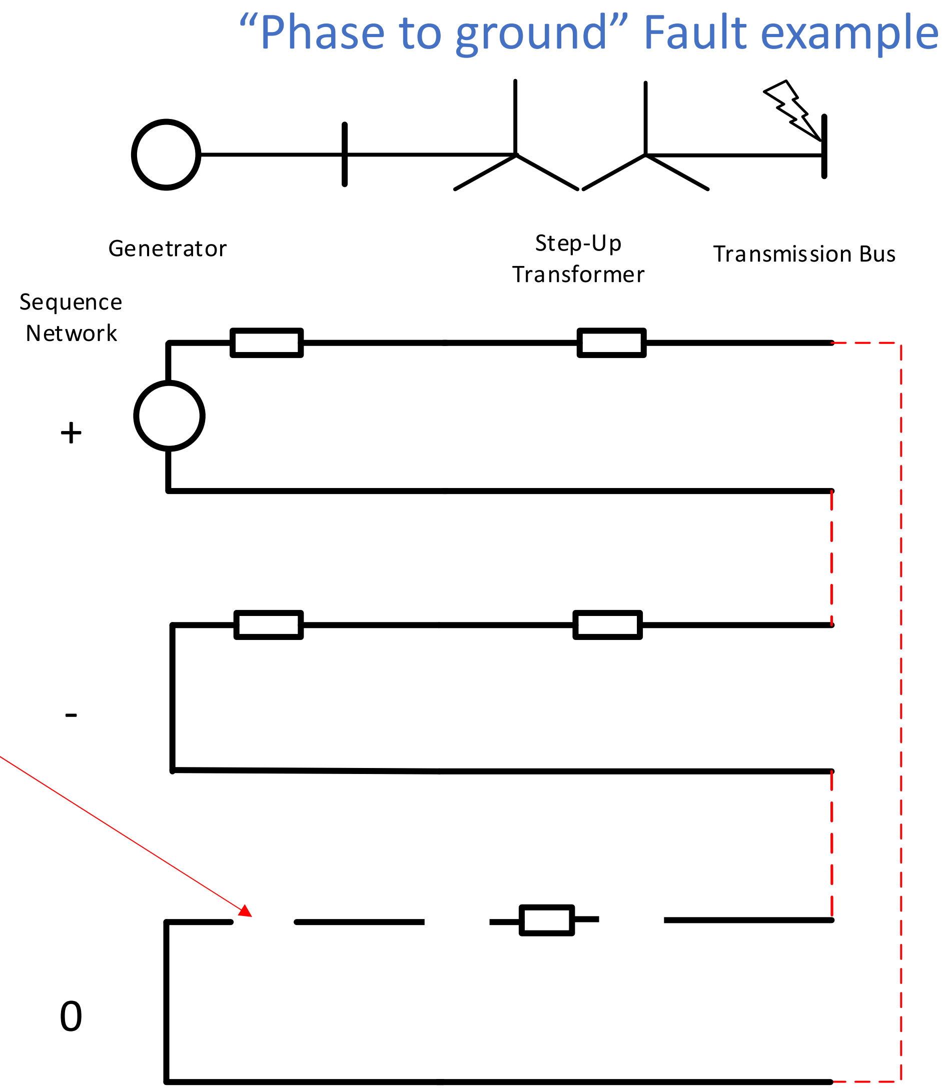


5. Example of a grounded system

Typical generators are rotating machinery that can easily be damaged be 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.



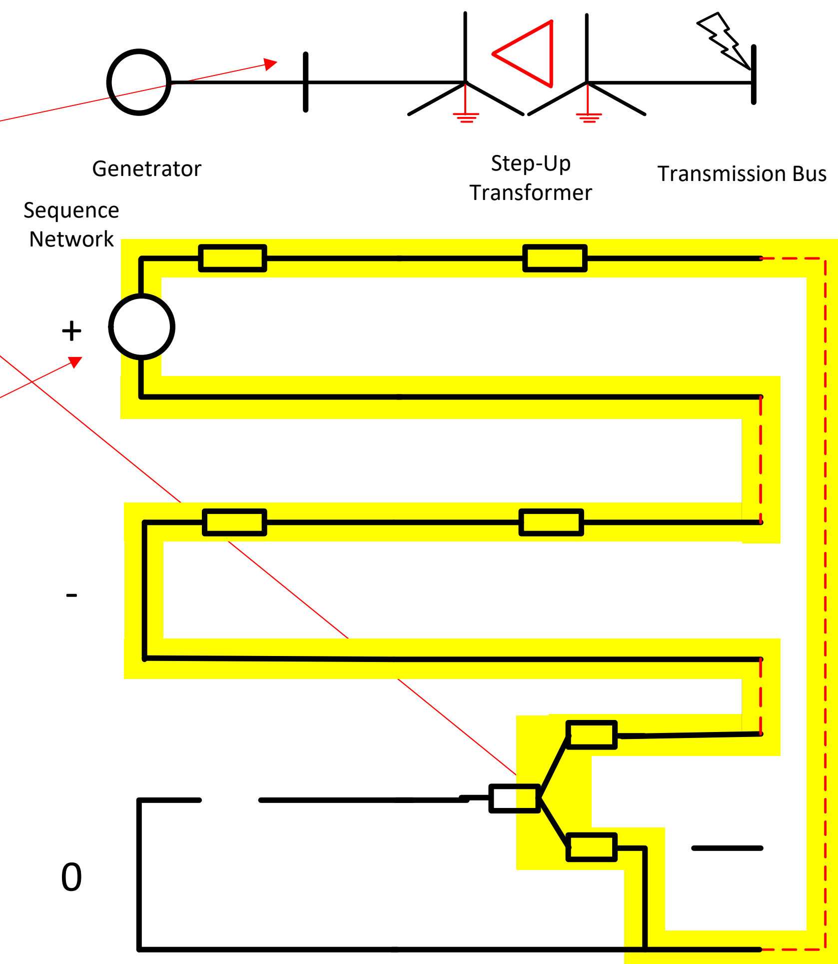
5. Example of a grounded system

“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**.

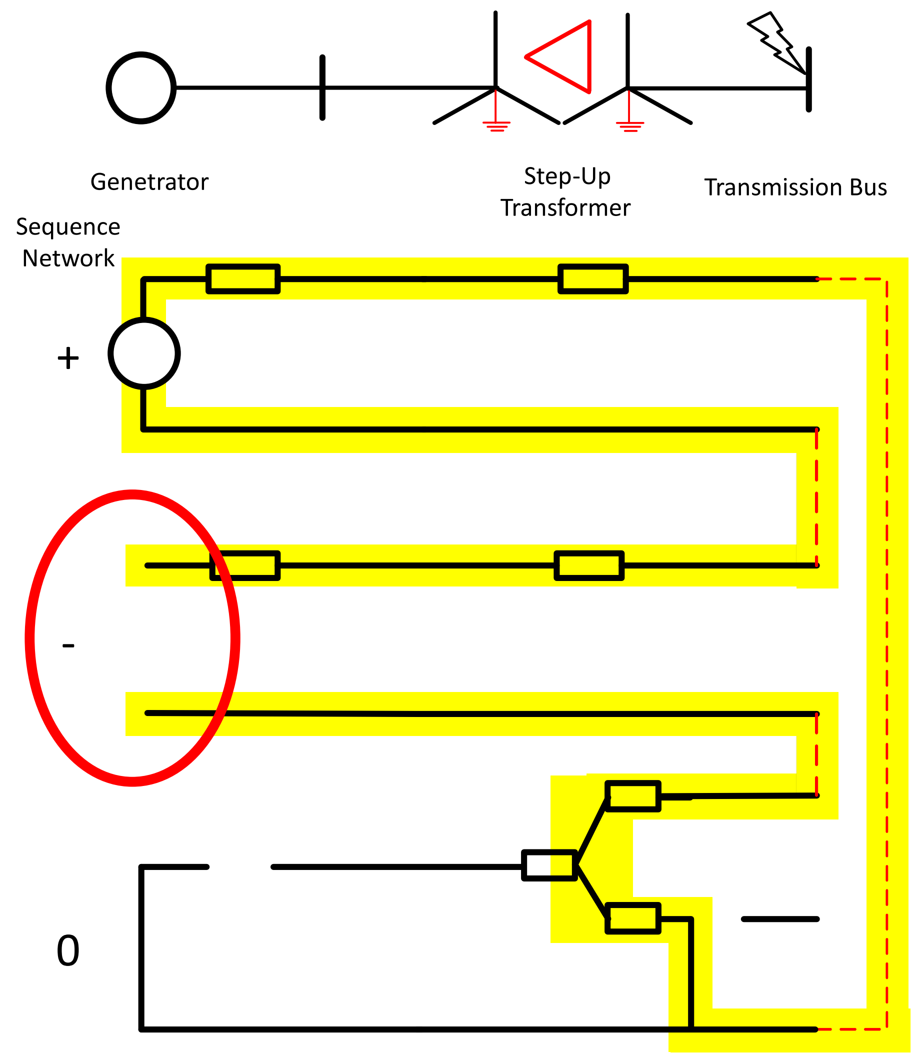


6. Example of a IBR connected to a ground system.

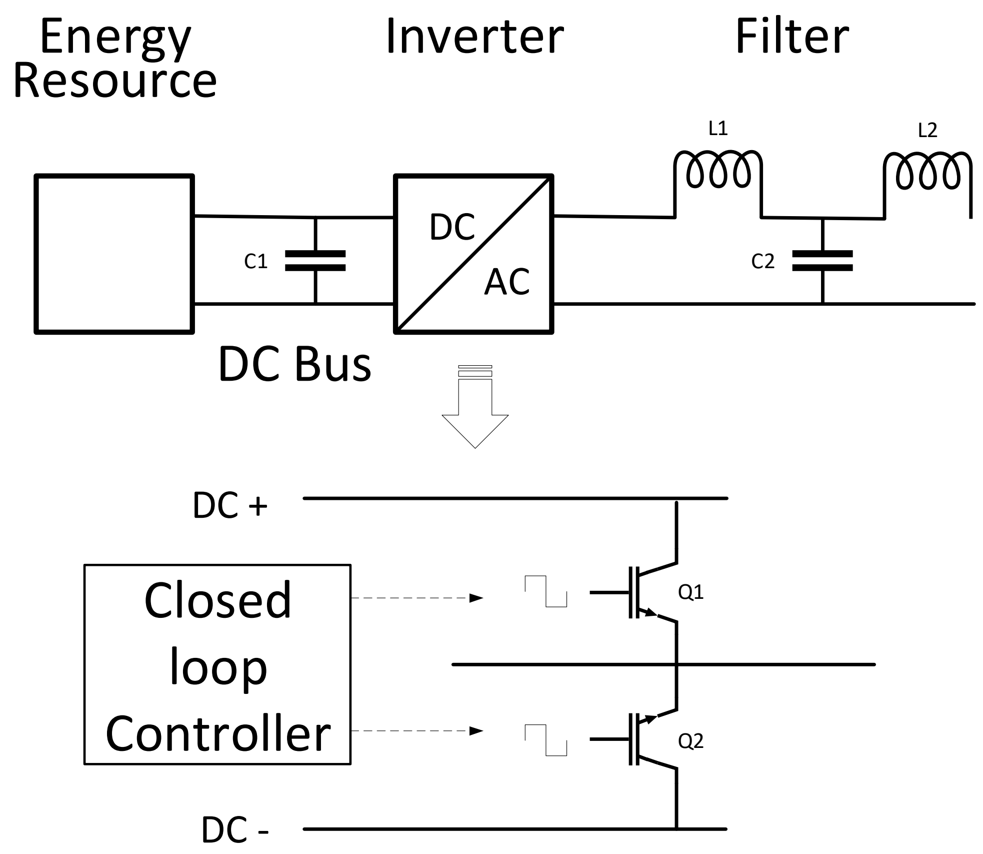
Typical Inverter Base Resources are built to only positive sequence current.

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.



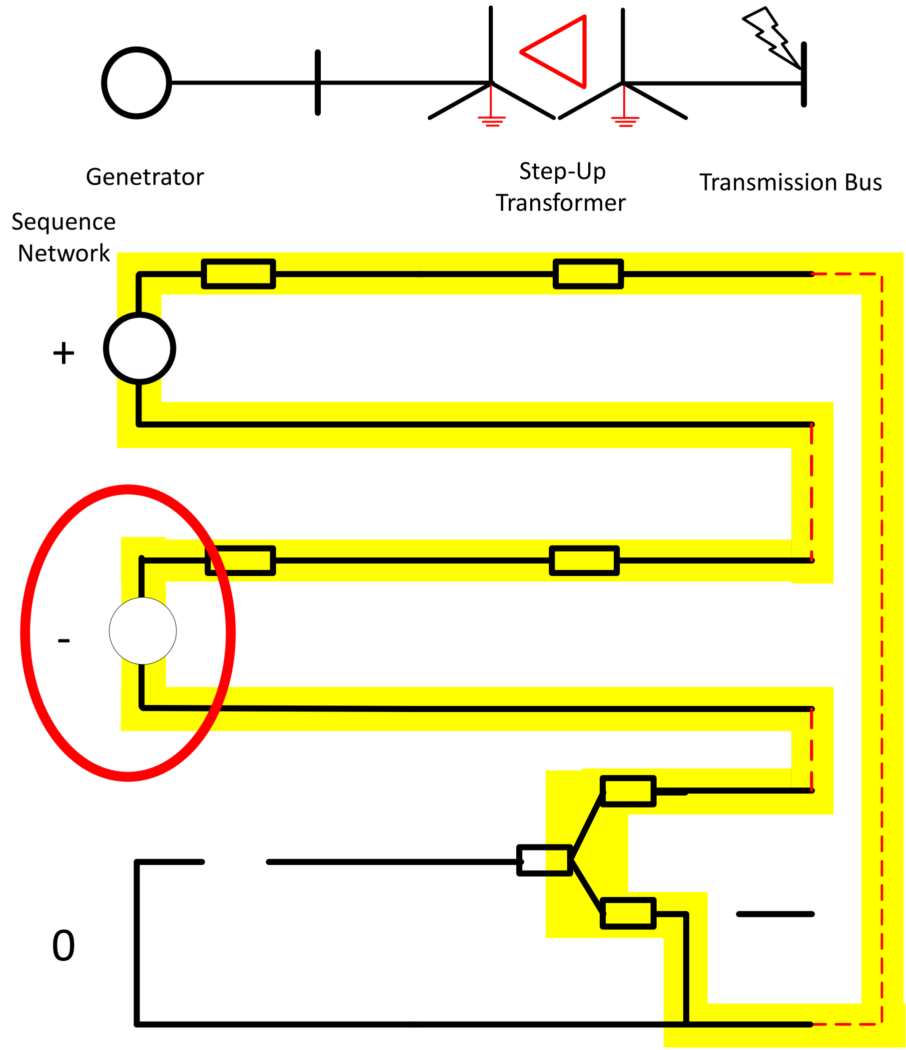
6. Example of a IBR connected to a ground system.

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

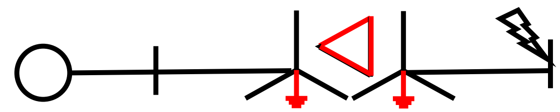
Since a ground transformer typically provide the closed path on transmission systems, only the negative sequence source the necessary to allow currents to flow.

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

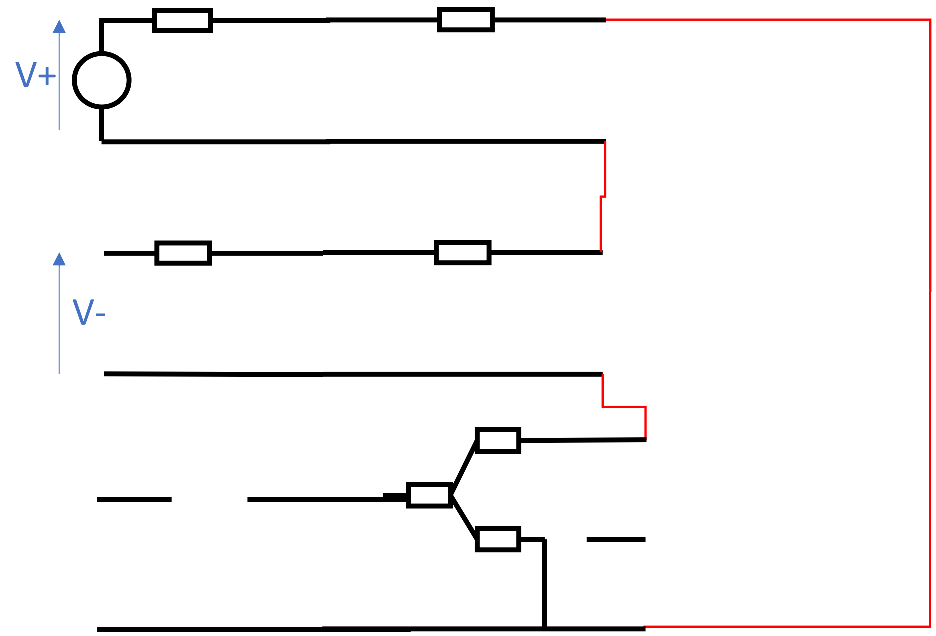
Since most of the system impedance is reactive, the angle in reference to the voltages will be close to 90 degrees.



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



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



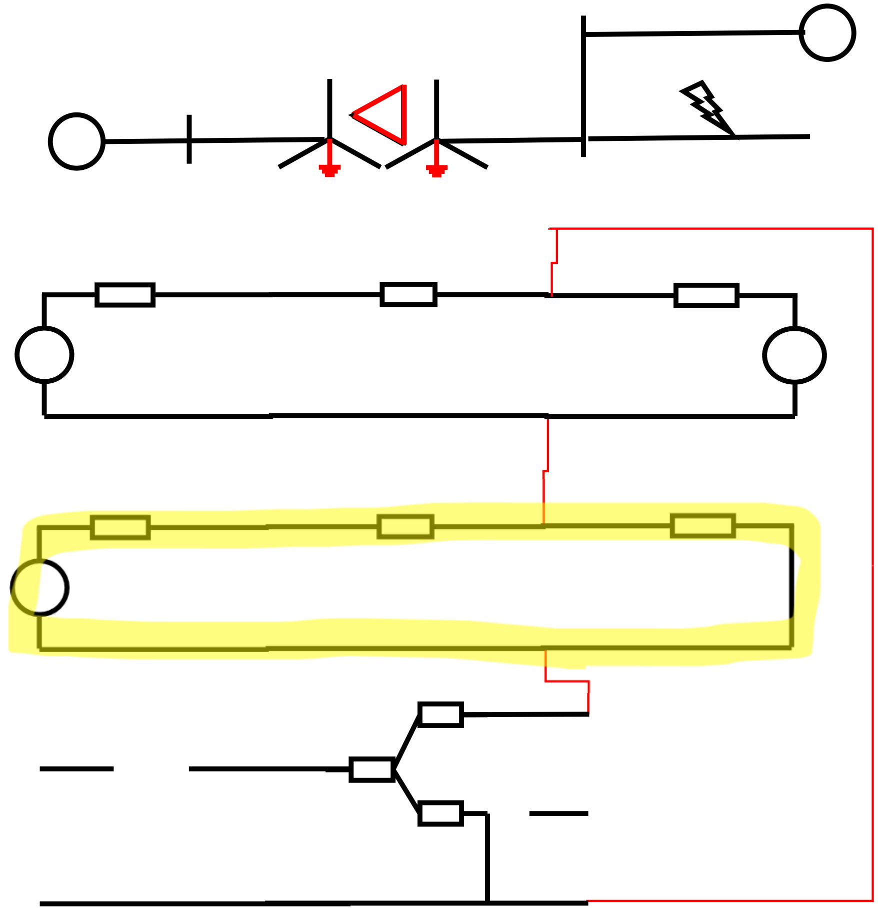
$I+ \; = \; I- \; = I_0 \; = 0$

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.

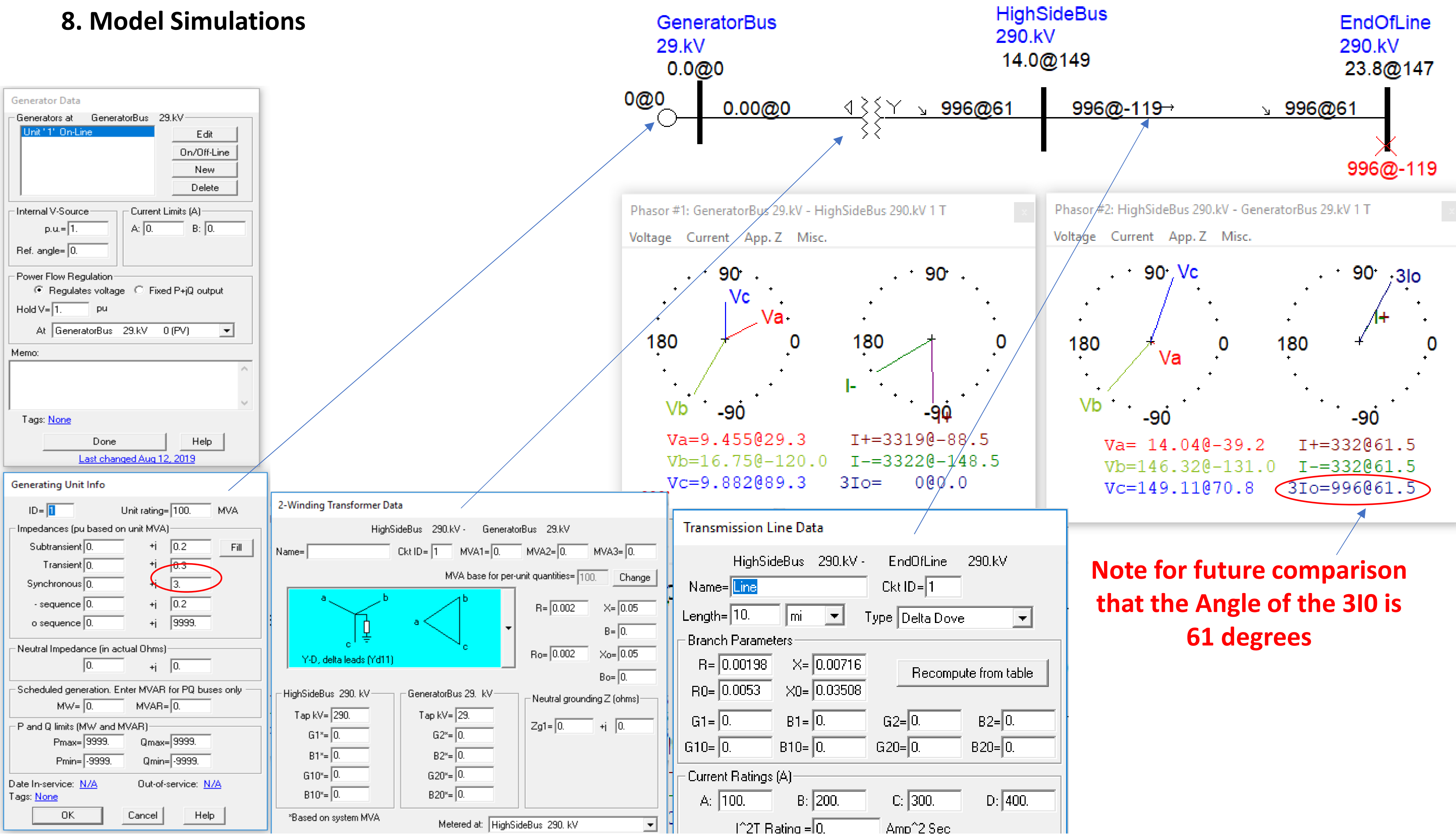
7. What could become problematic if the IBR do not allow for negative sequence or do not allow for enough of it, or do not control it adequately.

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.**

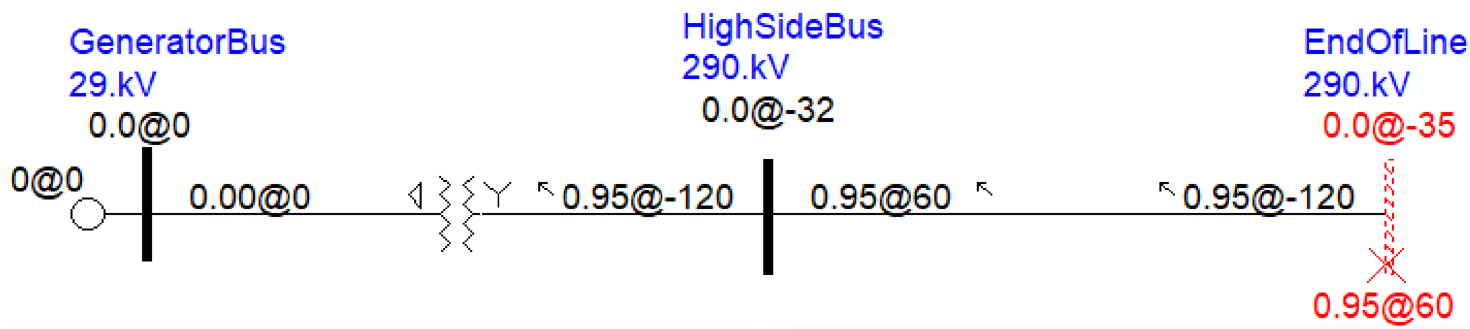
For this reason, the negative sequence source problem **must be addressed TODAY**.

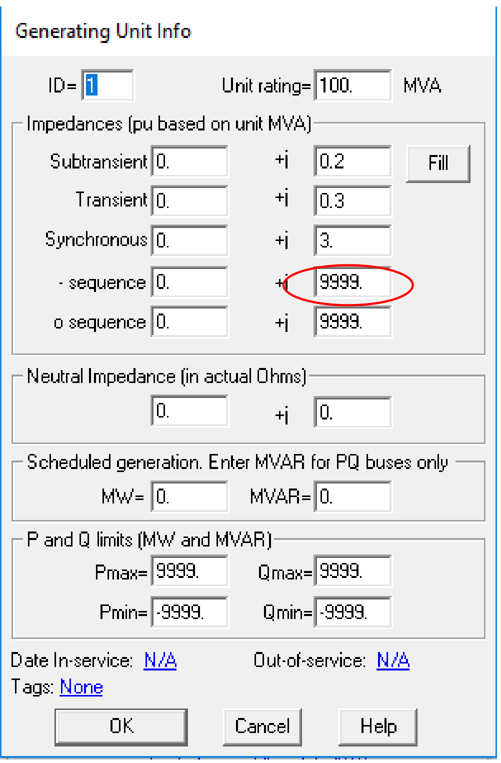
8. Model Simulations

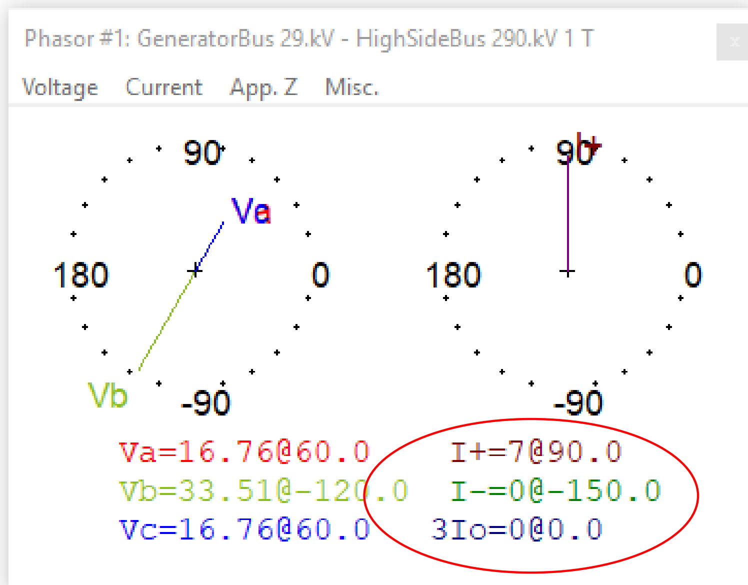


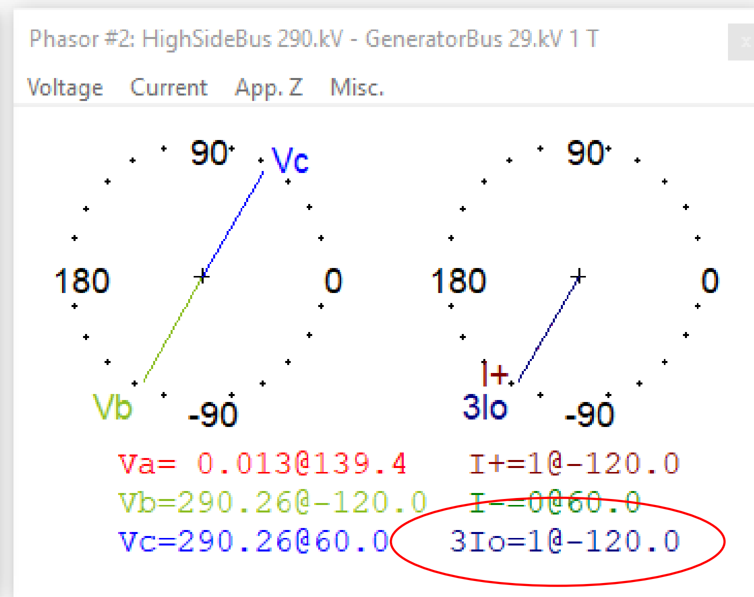
Note for future comparison that the Angle of the 3I0 is 61 degrees

8. Model Simulations



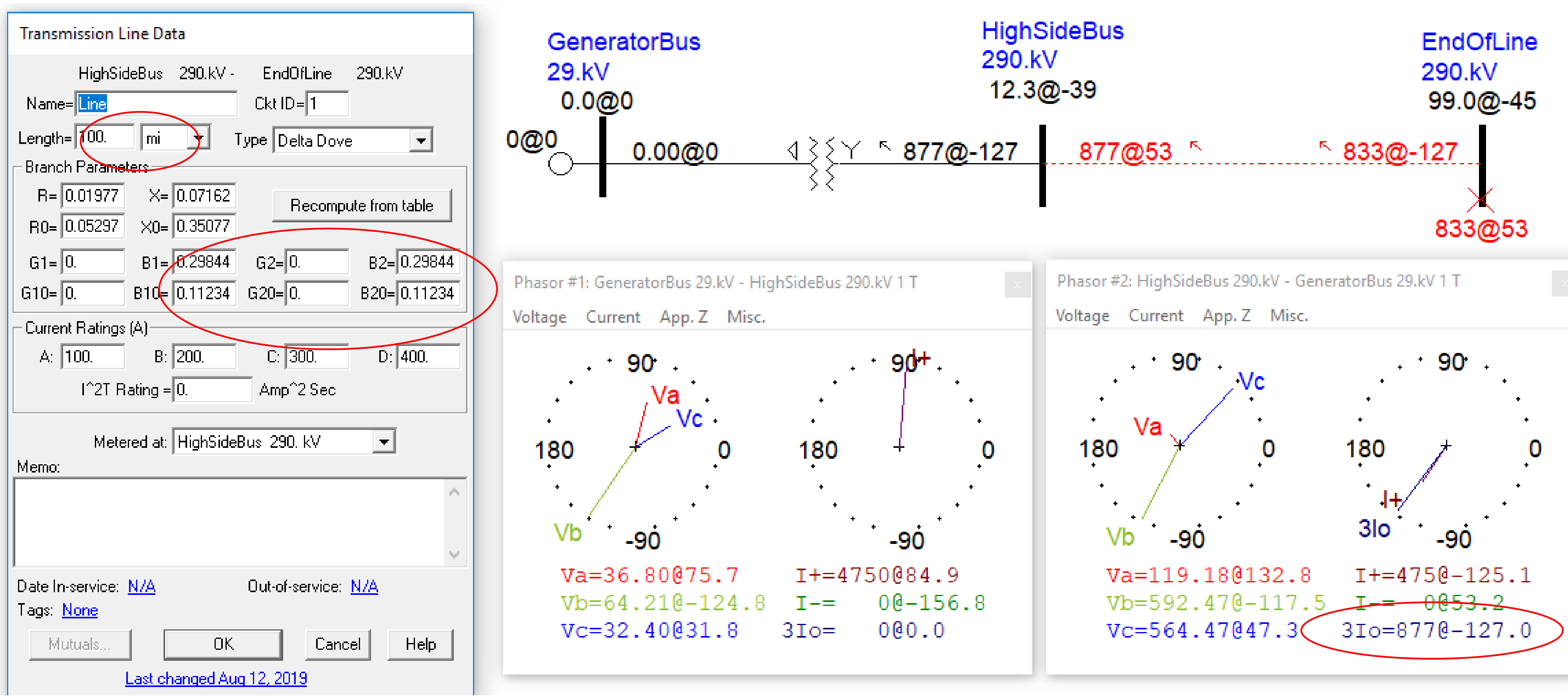






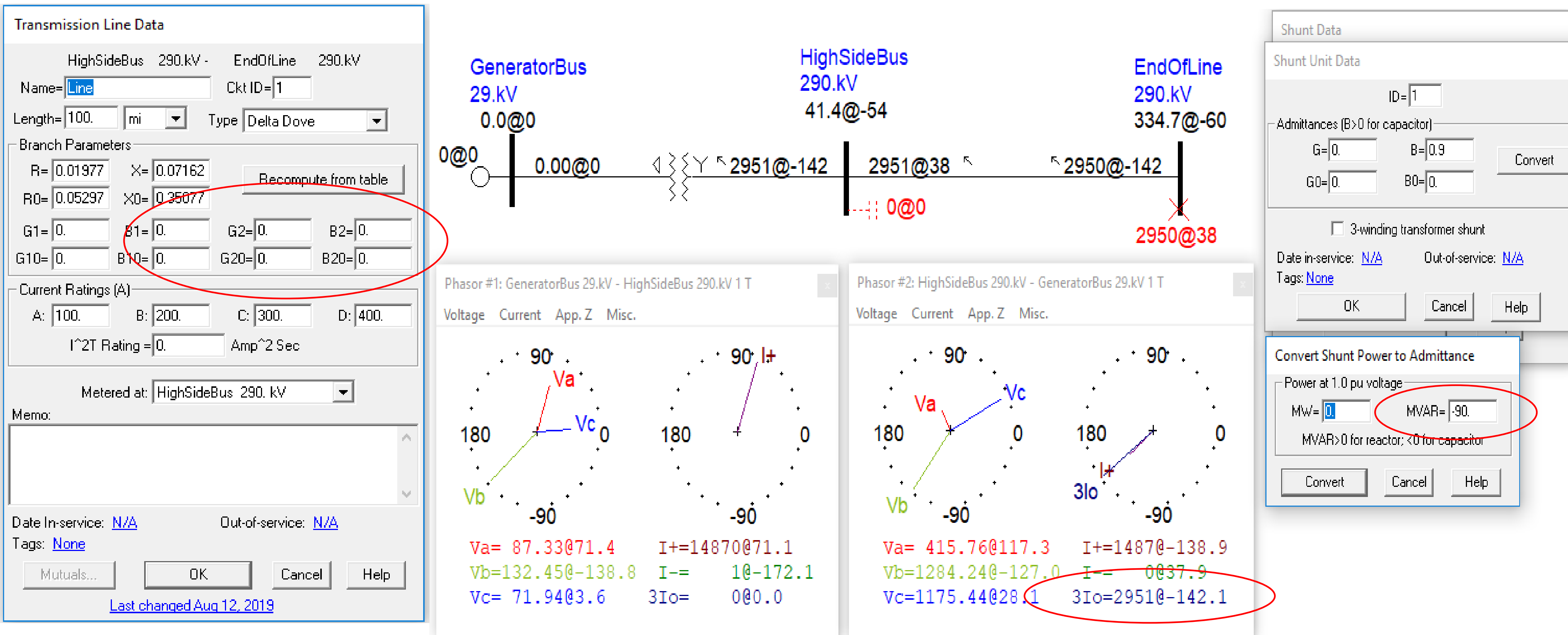
8. Model Simulations

The system shunt capacitance can provide the negative sequence path

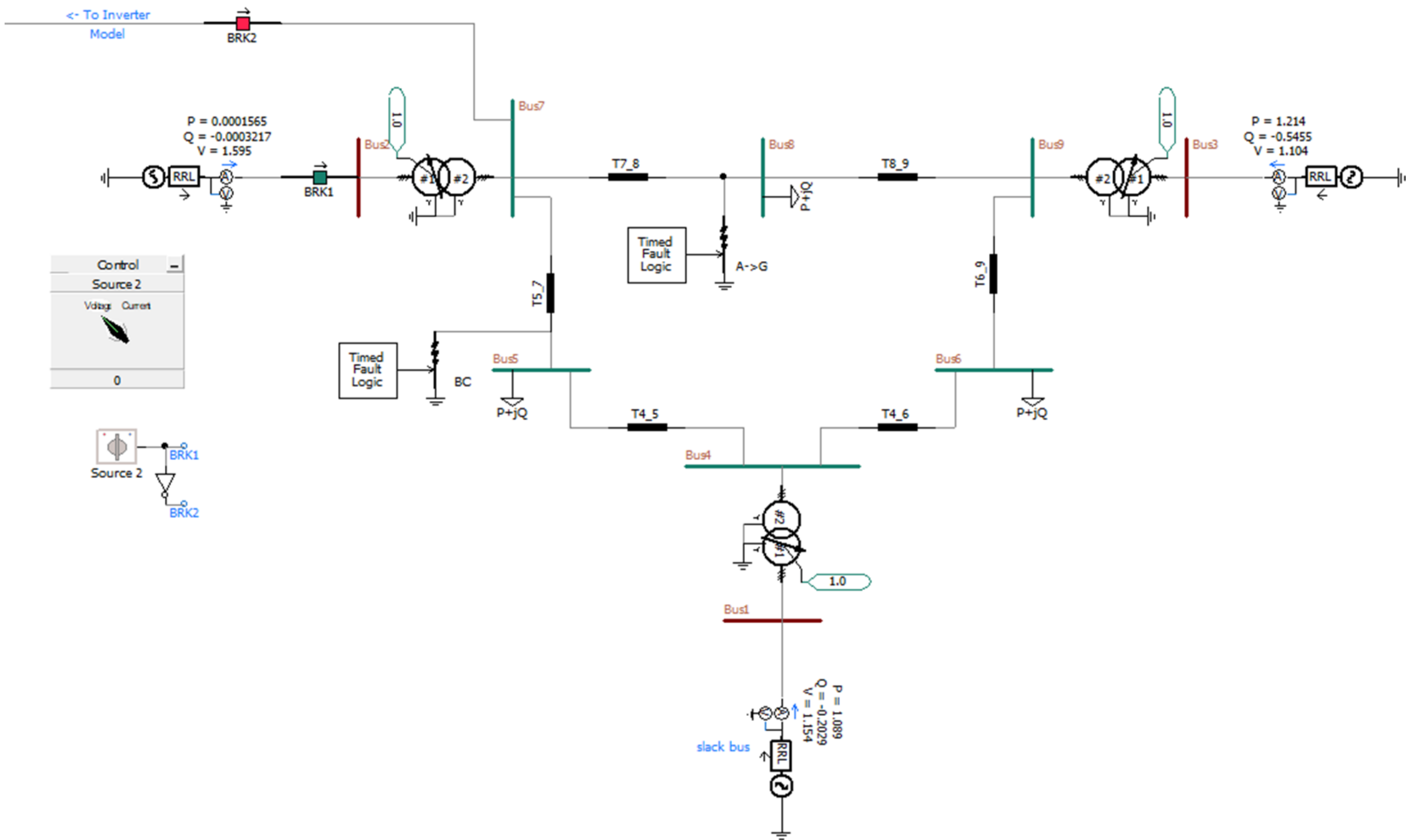


8. Model Simulations

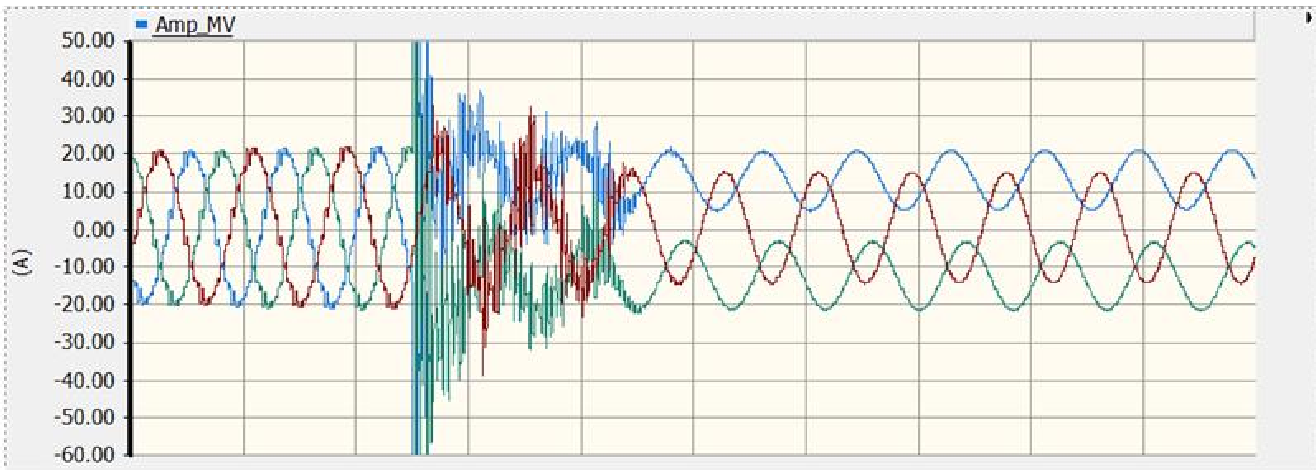
It acts similarly to shunt capacitor bank



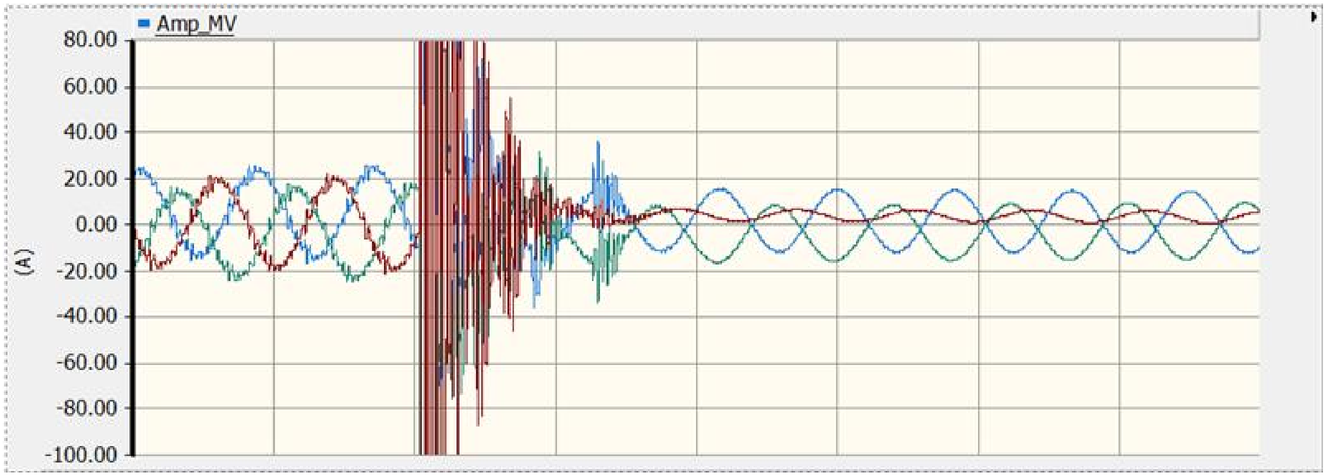
PSCAD Simulation



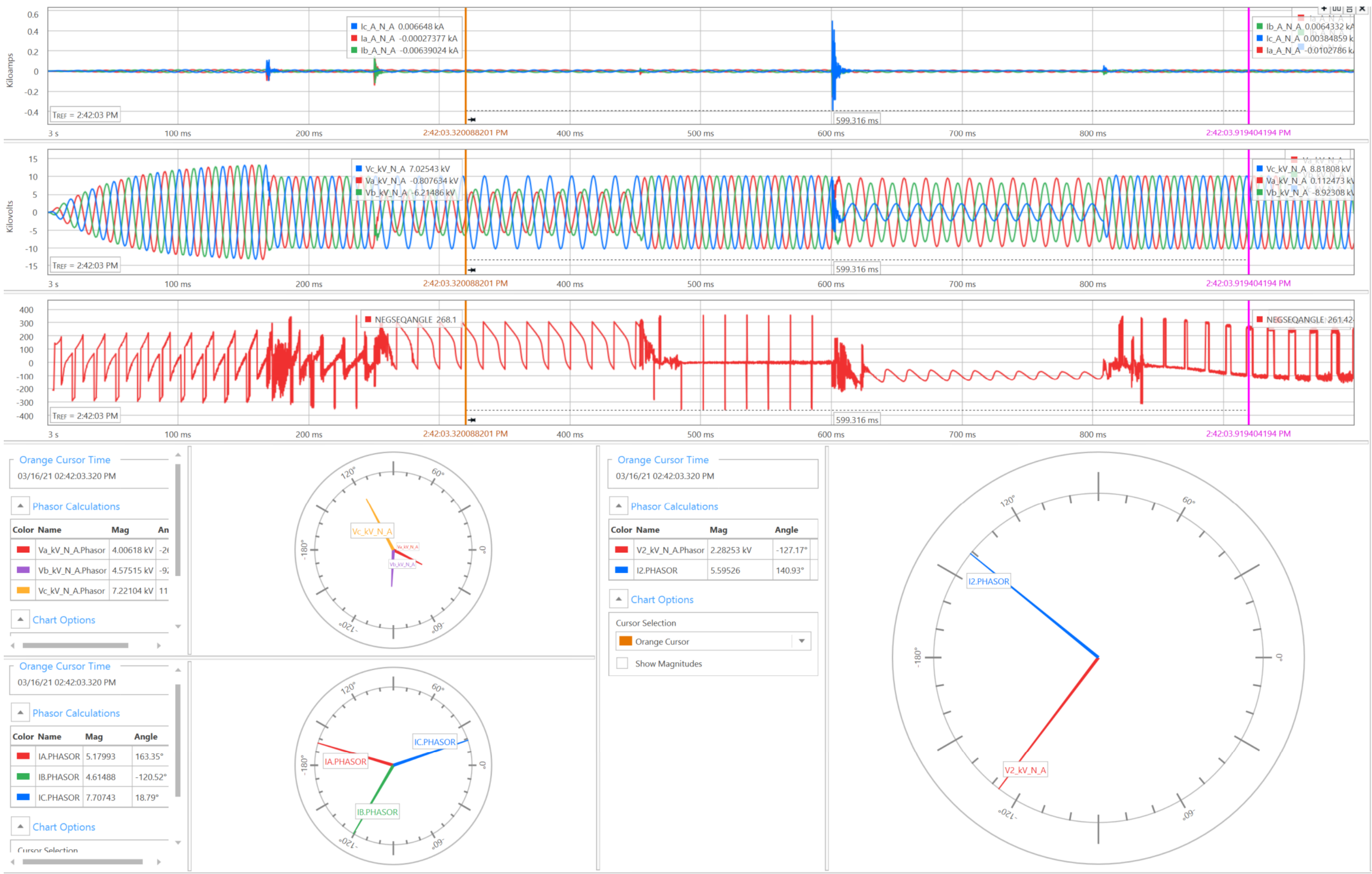
Inverter Output During Line-to-Ground Fault



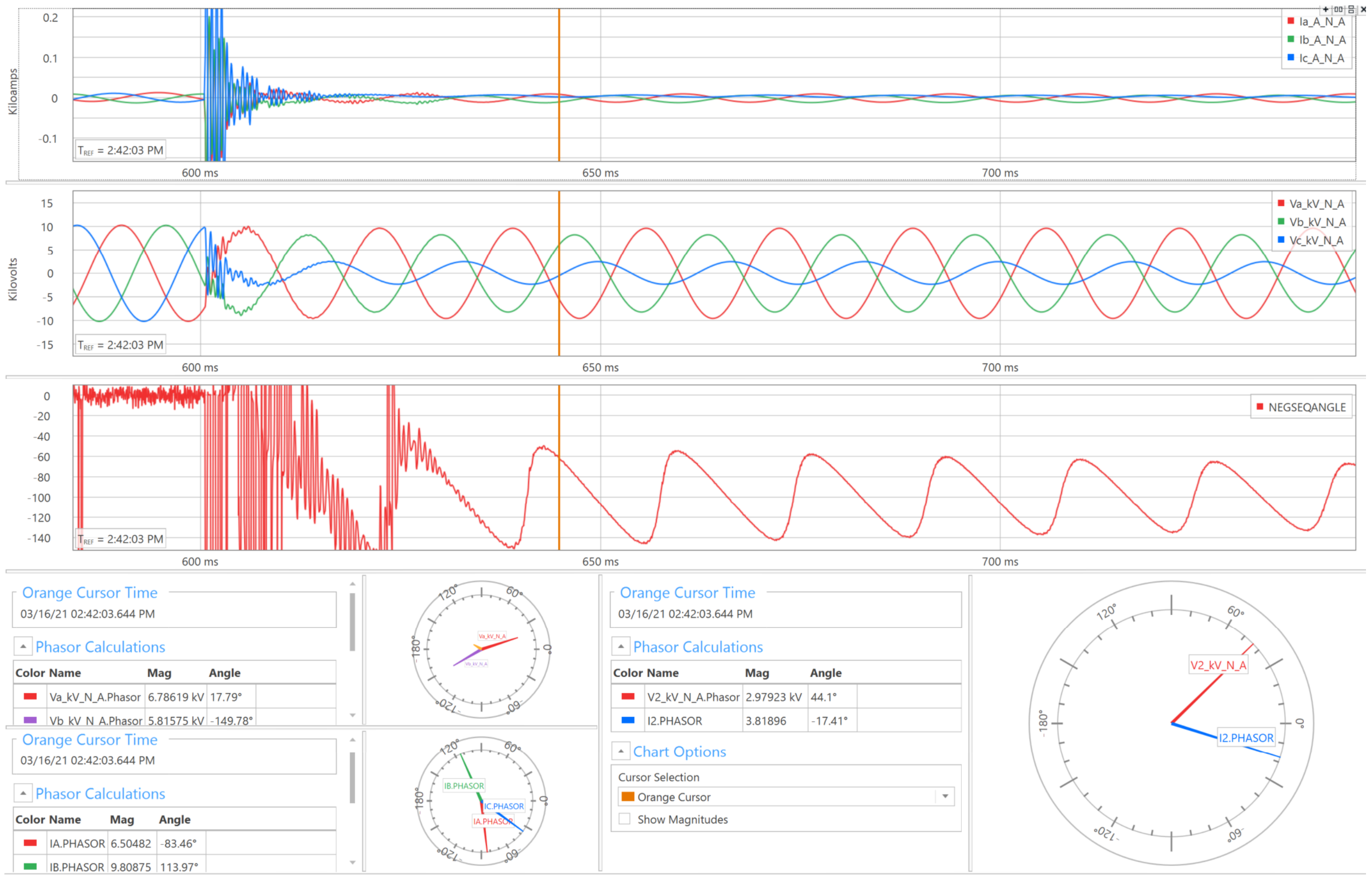
Inverter Output During Line-to-Line Fault



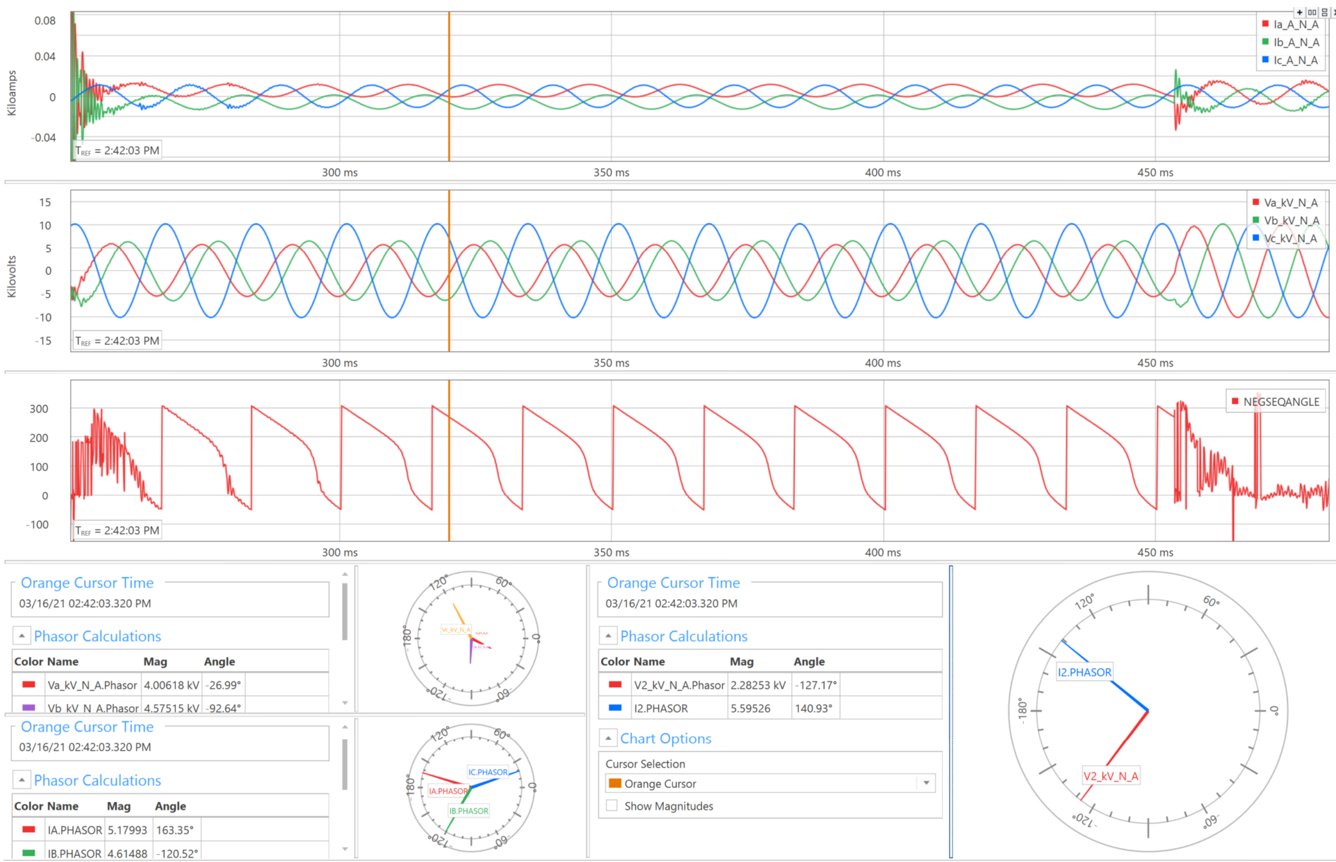
Inverter Output During L-g & L-L Faults



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 ?