Negative Sequence Current Contribution from Inverter Based Generation - How Will It Impact The New Zealand Power System?

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Abstract

Historically, the dynamic characteristics of inverter-based generation had little in common with the dynamic characteristics of synchronous generation, which presents a problem – How will grid protection operate with increasing amounts of inverter-based generation, given that the most commonly used protection elements are designed for the characteristics of synchronous machines?

In recent times, the control algorithms implemented in inverter-based generation have become more sophisticated; many inverters are now able to refine the dynamic characteristics to behave more like a synchronous machine during a fault event.

This paper explores the impact of changing the amount of negative sequence current contribution for a generator connected in Northland in two main areas:

1. What impact does negative sequence current contribution have on system voltages during an unbalanced fault?
2. Is the negative sequence current contribution from inverters sufficient to determine directionality of fault current, to the extent that it will reliably operate distance and directional earth fault elements?

When activating the negative sequence current gain in the inverter controller, the inverter was able to provide negative sequence current during asymmetrical faults, which consequently reduced the over-voltage observed on the healthy phase.

When negative sequence current contribution from inverters is enabled, it took longer for the inverter current output to settle after application of the fault. Despite this, we believe it is worthwhile to investigate further the impact that this increased settling time has on the protection devices commonly used on New Zealand's transmission network. Such analysis will help refine the amount of conservatism applied when reviewing the protection settings, especially when reviewing the adequacy of protection elements and associated settings on the wider network.

Introduction

The New Zealand government aims to achieve a carbon-neutral economy by 2050, by encouraging investment in renewable energy sources like solar, wind and battery energy storage, which rely on inverter-based technologies. Inverter-based technology exhibits dynamic characteristics distinct from those of synchronous generators, raising concerns about the effectiveness of traditional grid protection systems designed for synchronous machines.

Inverter-based technologies behaviour during power system faults is governed by their control logic and settings. While most inverters inject only positive-sequence current, some also inject negative-sequence current to better control the voltages on the AC side of the inverter. This negative-sequence current does not align with the fault current characteristics of synchronous machines, potentially causing false trips in protective relays. However, these negative sequence currents could potentially be used to reduce voltage rise on a healthy phase during asymmetrical faults, if tuned correctly.

The current Electricity Industry Participation Code does not specify any requirements around negative sequence current contribution as part of a generator's fault-ride through response.

This paper investigates the impact of negative-sequence current contribution from an inverter-based generator in the Northland region. The paper will start by introducing the site and typical settings for the generator and provide sample results illustrating the effectiveness of altering the inverter settings to provide differing amounts of negative sequence current during asymmetrical faults on the network. Final remarks are made on the suitability of negative-sequence current contribution in determining fault directionality to ensure the reliable operation of distance and directional earth fault protection elements.

Negative Sequence Current Injection Impact on Network Protection Systems

The following differences are highlighted between conventional rotating machines and inverter-based technologies [1]:

1. Rotation machines produce large faults currents with a small negative-sequence impedance path. Inverter-based technology typically have lower fault currents and negative sequence currents to minimise overvoltage on the DC bus capacitors.
2. Some inverter-based generators have a large negative sequence impedance, which can result in temporary over-voltages during unbalanced faults.
3. Conventional synchronous machines typically have an inertia greater than 3 s, allowing for grid support during faults. Inverter based technology can support the grid during faults, by implementing control algorithms designed to replicate the behaviour of a synchronous machine, however these algorithms rely on measurements made at the inverter terminals, and cannot respond instantly.

More recently, inverter control algorithms have evolved to provide a configurable amount of negative sequence current injection during unbalanced faults, to help reduce the magnitude of over-voltages on the healthy phases.

However, this current injection could adversely impact the directional protection elements currently installed on the network. This is due to the directional elements typically using negative sequence components to polarise the relays. This polarising of the directional elements is performed by the 32Q relay element and uses the following calculation to determine polarity [2]:

$$Z_2 = \frac{|V_2|}{|I_2|} \cos(\angle V_2 - \angle I_2 - \angle Z_1)$$

Where:

- Z_2 is the negative-sequence impedance
- V_2 is the negative-sequence voltage
- I_2 is the negative-sequence current
- Z_1 is the positive-sequence impedance
- $\angle$ is the angle of the given parameter

This equation considers the magnitude and angle of the current passing through the measurement point. An example network is seen in Figure 1. For a forward fault, the negative sequence impedance is seen as the negative source impedance $(-Z_s)$. For a reverse fault, the negative sequence impedance is seen as $(Z_L + Z_R)$. Therefore, under normal conditions, a negative Z_2 value would represent a forward direction and a positive Z_2 value would represent a reverse direction as depicted in Figure 2.

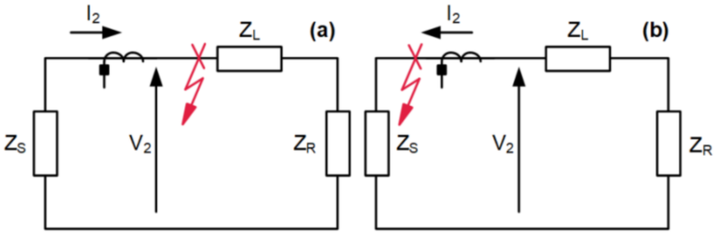

Figure 1: Example of a forward fault (a) and reverse fault (b) [3]

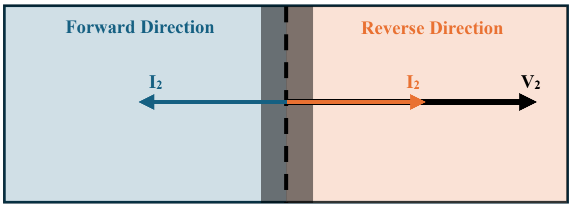

Figure 2: Relationship between V2 and I2 for forward and reverse faults

Based on this simplified theory it should stand to reason that by utilising the negative-sequence current injection of the inverter-based technologies during unbalanced faults would impact the measurement directionality of the negative sequence current (I_2) and subsequent directionality of the fault.

Model setup and assumptions

A model was setup in PSCAD[1], which has the required electromagnetic transient (EMT) simulation engine required to perform the detailed assessment. A simplified single line diagram layout is seen in Figure 3 for the network representation and the following list of equipment:

- 220 kV Grid Connection
- 2x 220/33 kV YNd3 Transformers
- 2x Earthing Transformers with 20 Ω Earthing Resistor
- 33 kV Network
- 33 kV Load
- 33 kV Synchronous Generator Connection (simplified representation)
- 33 kV Inverter-based resource

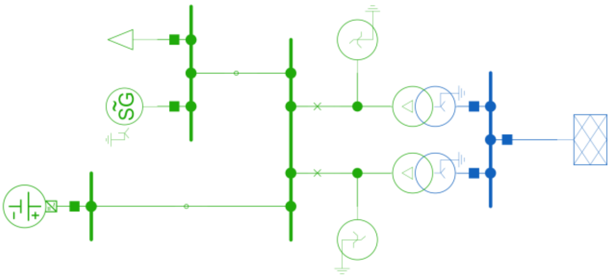

Figure 3: Simplified model setup

An important note is that the 33 kV network (green) is non-effectively earthed where an earth connection is made through a zig-zag transformer and neutral earthing resistor (NER). Thereby causing the 33 kV network voltage on the healthy phase to increase up to 1.73 pu for any direct two-phase-to-ground (2PHG) fault on the 33 kV network. An example of this phenomenon is shown in Figure 4 where a 2PHG fault is applied at t=3 s and remains in a faulted state for another 3 s.

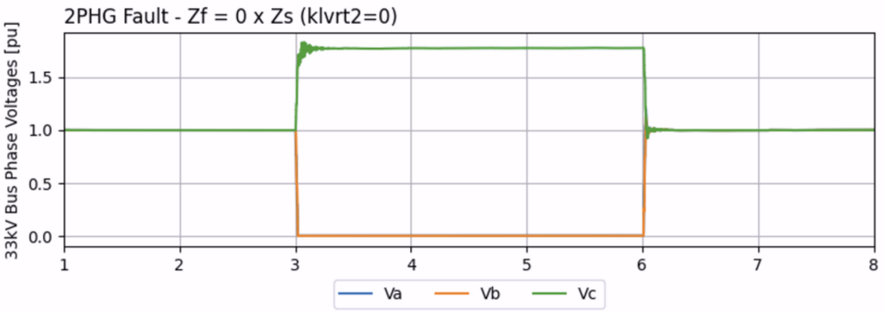

Figure 4: Example of a direct 2PHG fault with phase C (green) being the un-faulted (healthy) phase

Inverter fault current contribution and its effect on the network voltages

The inverter current contribution during asymmetric faults can be performed in three different methodologies for the specific inverter being assessed [4]:

- Balanced positive sequence current based on the positive sequence voltage
- Balanced positive sequence current based on the minimum phase-to-phase voltage
- Unbalanced current based on the positive and negative sequence voltage.
    - Positive sequence current injection: $I_{q,1} = I_{q,prev} + K_{lvrt,1} \times (V_{set} - V_1)$
    - Negative sequence current injection: $I_{q,2} = K_{lvrt,2} \times V_2$

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[1] PSCAD: Power Systems Computer Aided Design

Additionally, it is noted that the inverter prioritises negative sequence current ($I_{q,2}$) first, then positive sequence current ($I_{q,1}$) and lastly the active positive sequence current ($I_{d,1}$).

For these studies:

- The unbalanced current based approach was used where both the positive and negative sequence current injection was calculated. In so doing, it is expected that the inverter will actively reduce the high voltage on the healthy phase during asymmetrical faults.
- The positive sequence gain ($K_{lvrt,1}$) was set to 2.0.
- The negative sequence gain ($K_{lvrt,2}$) was tested at 0, 0.5, 1.0 and 2.0, to observe impact of varying amounts of negative sequence current injection for the same fault.

Assessment parameters

The following variables were fixed during the assessment:

- Source Impedance (Zs) – Calculated using a short-circuit ratio of 3 and X/R ratio of 7
- Fault Start Time: 3 s
- Fault Duration: 3 s
- Faut Location: 33 kV bus
- All inverter settings and configuration were left with their default values.

The following variables were iterated over during the assessment:

- Fault Types (2PHG, 2PH, 1PHG)[2]
- Fault Severity (Multiplier in relation to Zs)
    - 0 – Zero Impedance Fault
    - 1 – Typically relates to a positive-sequence residual voltage of 50 %
    - 2 – Higher impedance fault typically with a positive sequence residual voltage of 66%
- The inverters negative sequence gain ($K_{lvrt,2}$)

This study will focus on asymmetrical faults on the 33 kV network while assessing the inverter current output and effect of the voltages on the 33 kV network.

Results

The results present a summary of the zero and high impedance faults with two different negative sequence gains.

Zero Impedance Fault Assessment

Analysing the results during a zero impedance asymmetric fault indicated that by implementing a negative sequence current gain, the voltage on the healthy phase can be considerably reduced as seen by comparing the results in Figure 5 and Figure 6. The initial spike is a clear indication of fault current being a controlled response from the inverters and thus takes at least half a cycle (10ms) to respond to faults.

The result seen in Figure 5 shows positive sequence current injection (**Iseq:1**) during the fault with no negative sequence current injection (**Iseq:2**). Figure 6 shows a high negative sequence current injection due to the large, unbalanced voltage, thereby causing V_C to reduce after the

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[2] 2PHG: Two-Phase to Ground
2PH: Two-Phase
1PHG: Single-Phase to Ground

initial spike at fault inception. Additionally, the current contribution from the inverter takes a longer time to settle, which may impact the operation of certain protection elements.

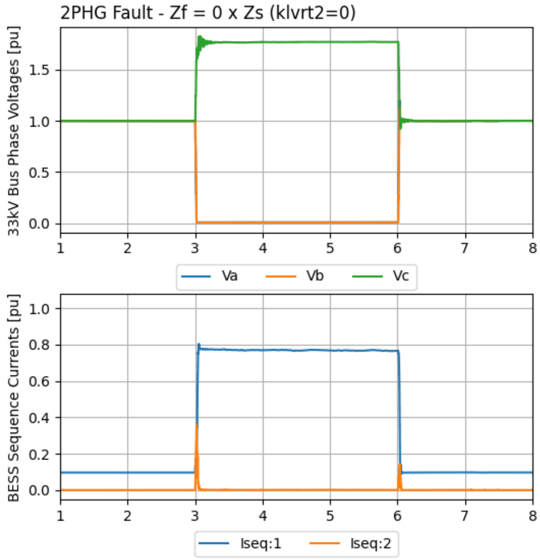

Figure 5: Zero impedance – 2PHG fault with no negative sequence current injection.

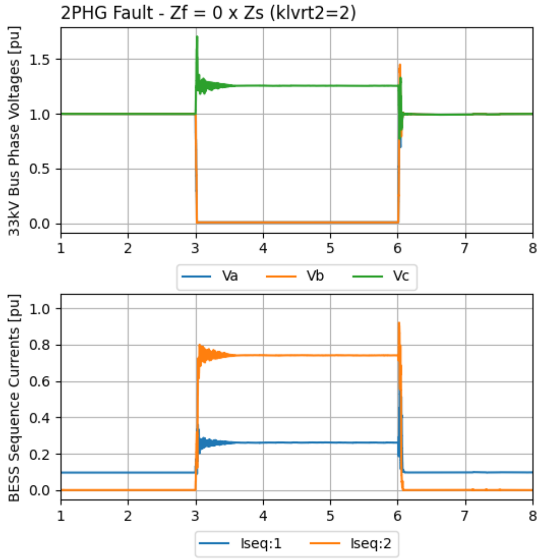

Figure 6: Zero impedance – 2PHG fault with negative sequence current injection.

High Impedance Fault Assessment

Analysing the results during a high impedance asymmetric fault indicated that by implementing a negative sequence current gain, instability to the network voltage can be a possibility if the gain is not tuned correctly, with little benefit to reducing the healthy phase voltage. These results are seen in Figure 7 and Figure 8.

However, analysing the results at a lower negative sequence gain showed a more stable result with only a minor improvement (<0.01 pu) to the healthy phase voltage. This indicates that negative sequence current injection is ineffective for high-impedance faults based on this particular inverter control algorithm.

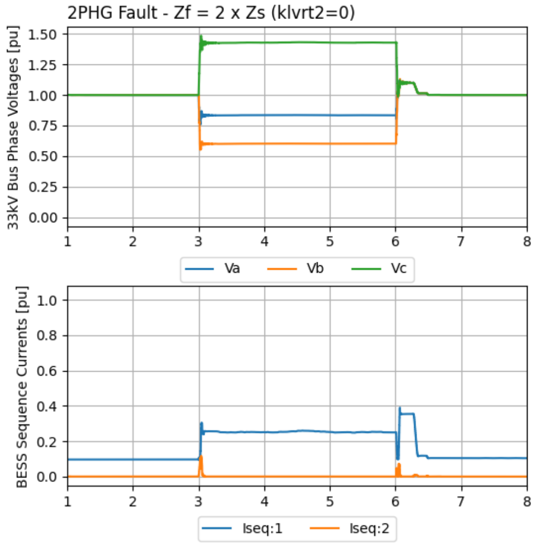

Figure 7: High impedance – 2PHG fault with no negative sequence current injection.

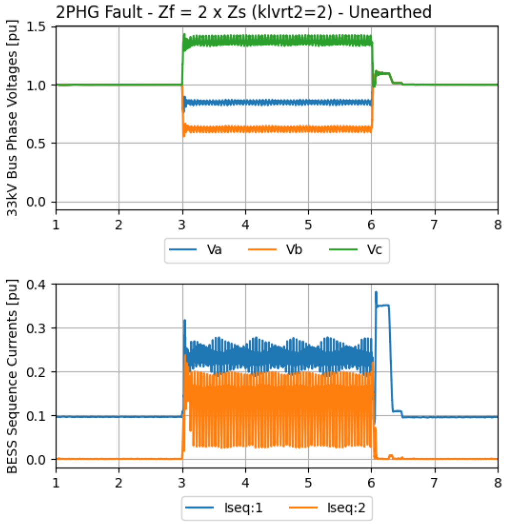

Figure 8: High impedance – 2PHG fault with negative sequence current injection.

Further investigation is required to confirm the impact of these oscillations on protection relays. Protection relays implement filtering that may assist in cleaning the voltage and current signals seen in Figure 6, so these oscillations may be of little consequence.

Previous studies showed that the earthing arrangement of the inverters have a significant impact on the stability of the inverter output when performing the negative sequence current injection. The original setup, where the inverter and associated unit transformer had a direct low-voltage (LV) earth connection, led to circulating currents. This made it difficult to control the negative sequence current and resulted in network voltage instability.

Response from a Synchronous Generator during Asymmetrical Faults

A synchronous generator has a response to asymmetric faults which is related to its rotating mass and physical configuration. The physical configuration of the stator windings creates a back EMF on the rotor. If one phase has a low voltage event, the magnetic field drops at a particular point in the machine's rotation, causing a larger amount of current to flow in that phase, thereby contributing to the fault based on the voltage imbalance they experience. The response from the modelled synchronous generator during a zero impedance and high impedance fault is seen in Figure 9 and Figure 10 respectively. The response indicates that the synchronous generator naturally responds to the voltage imbalance by providing a steady negative current contribution with the positive sequence providing the required network support.

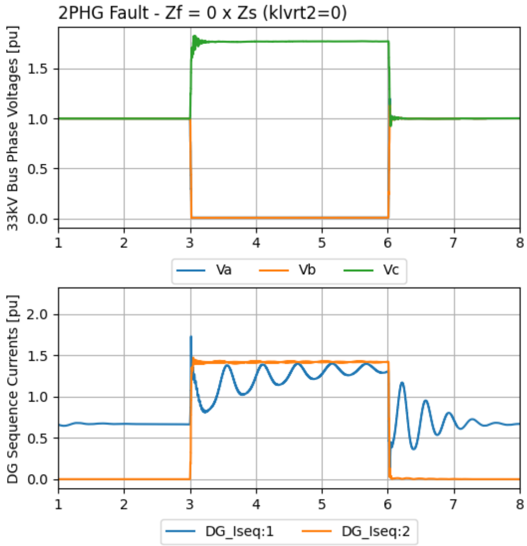

Figure 9: Synchronous Generator response during zero impedance – 2PHG fault

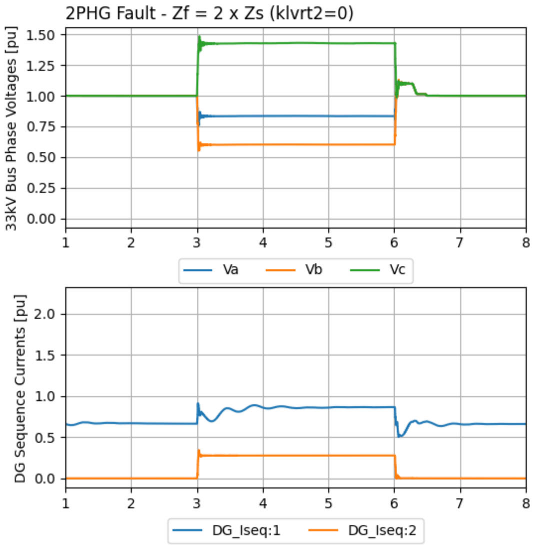

Figure 10: Synchronous Generator response during high impedance – 2PHG fault

Further Studies

A further set of studies was performed to assess the capability of the negative sequence current injection during an asymmetrical fault on the 220 kV network. This was limited to a single-phase-to-ground fault as this equates to a two-phase-to-ground equivalent on the 33 kV system with a start-delta transformer.

The results seen in Figure 11 and Figure 12 indicate that a negative sequence current gain of around 0.5 could reduce the healthy-phase voltage by almost 10%. Negative sequence gains higher than this caused some unwanted results. Therefore, careful consideration and tuning of the negative sequence current gain is important to ensure system stability.

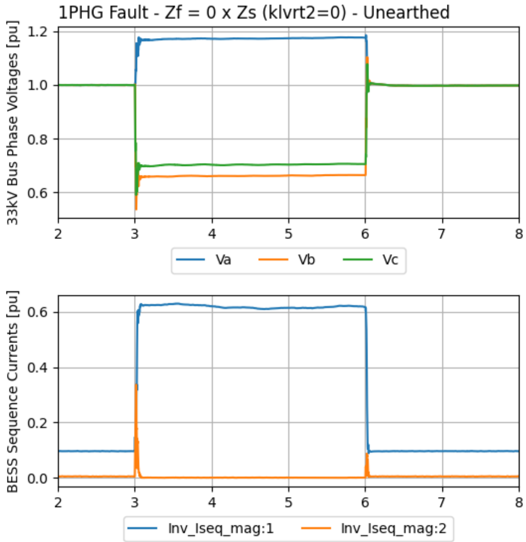

Figure 11: Zero impedance – 1PHG fault at 220 kV bus with no negative sequence current injection

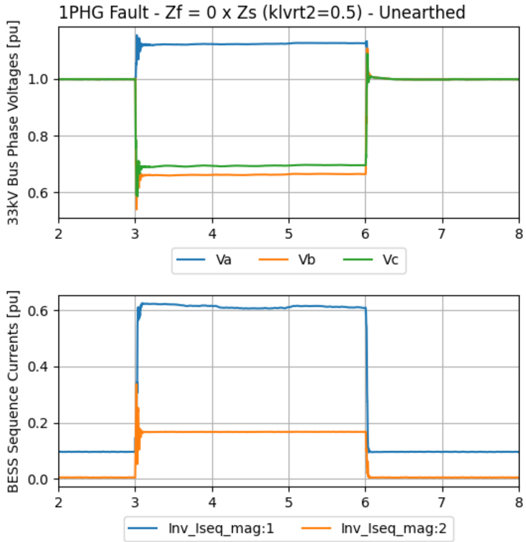

Figure 12: Zero impedance – 1PHG fault at 220 kV bus with negative sequence current injection

A comparison of the inverter and the synchronous generators' negative sequence current angles were also investigated during this study. The results are presented in Figure 13 and Figure 14. The current angles displayed in the figures are based on the negative sequence voltage. Thereby indicating the angle difference between the negative sequence voltage and current.

It is seen that when no negative sequence gain is used, the inverter angle is quite different from the synchronous machine. This is understandable as there should be no negative sequence current and therefore, no current reference to measure. However, when using a negative sequence current gain, the inverter and synchronous generator has a similar angle response during the fault. This response indicates that the protection polarity may not necessarily be a problem when using negative sequence gains. Based on these results, further studies are planned to confirm whether directional elements can be configured to operate correctly.

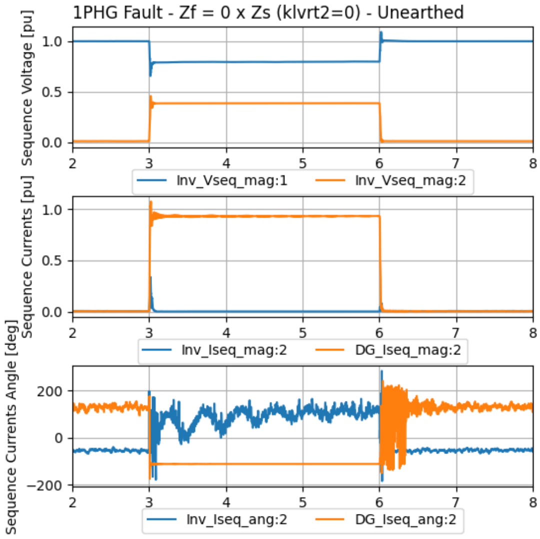

Figure 13: The Inverter (INV) and the Synchronous Machine (DG) Sequence phase angles during 1PHG fault at 220 kV bus with no negative sequence current injection.

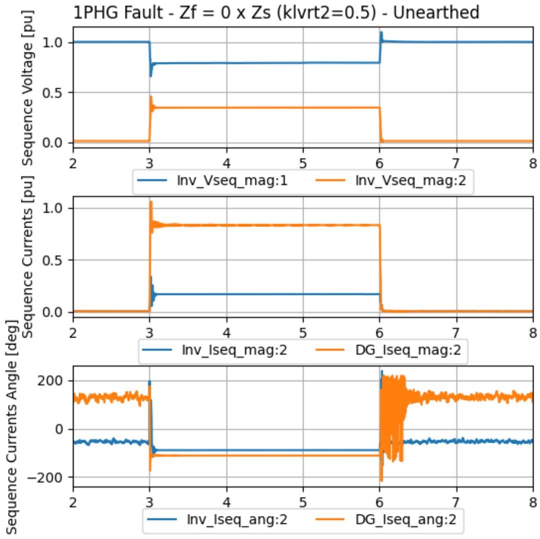

Figure 14: The Inverter (INV) and the Synchronous Machine (DG) Sequence phase angles during 1PHG fault at 220 kV bus with negative sequence current injection.

Final thoughts

The studies in this report assessed the impact of negative sequence current injection based on an inverter model provided by the equipment manufacturer. The results indicated that the negative current injection during zero impedance faults reduced the healthy phase voltage considerably. However, during high-impedance faults, the healthy phase voltage only reduced by a small amount. Additionally, voltage instability may be caused when setting the negative current gain too high or not having an adequate LV earthing arrangement. Other inverter-based technology manufacturers may calculate the negative sequence current contribution differently and respond with different results during high impedance faults.

There is a potential for inverter-based technologies to impact the measurement directionality of the negative sequence current (I_2) and subsequent directionality of the fault. At present, the rules and regulations applicable in New Zealand provide no guidance on how negative sequence current contribution is to be set for inverter-based resources.

The results comparing the synchronous generator and the inverter regarding their negative sequence current angles, indicate that the inverters have a possibility of acting similar to synchronous generators during the fault when using a negative sequence current gain. Accordingly, it may be possible to prove that existing distance-based protection schemes will reliably operate, without major protection upgrades on the wider grid.

However, further investigations will be necessary to prove that the inverter response can be correctly interpreted by the relay models which are commonly used in New Zealand.

References

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