# Impact of German Grid Code on Negative Sequence-based Directional Protection for Grids with Grid-Forming IBRs

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***Abstract*— High penetration of inverter-based resources (IBRs) challenges negative sequence based directional protection, which assumes synchronous generator fault behavior. IBRs, interfaced through converters, provide limited negative or no negative sequence current and unexpected phase relationships, causing maloperations of directional elements. The German VDE-AR-N 4120 standard mandates proportional positive- and negative-sequence current injection during faults or abnormal voltage condition for grid support. This paper evaluates the impact of VDE-compliant controls on negative sequence directional schemes using EMT simulations for IBRs with and without VDE compliance under varying sequence current limiting strategies. Results show improved fault improved operation and accuracy of directional elements for systems with IBR adhering to VDE grid codes, while also exposing the impact of varying implementation of the grid code across different vendors.**

***Keywords—unbalanced faults, fault-ride-through, inverter-based resources, directional protection***

## I. INTRODUCTION

The increasing penetration of inverter-based resources (IBRs), such as wind turbine generators, photovoltaic plants, batteries, etc. has transformed the operational characteristics of modern power systems. Unlike conventional synchronous generators (SGs), which provide predictable fault current contributions, IBRs interface through power electronic converters and exhibit fault responses governed by control algorithms rather than machine physics [1], [2]. This introduces significant challenges for traditional protection schemes, which were designed under assumptions of high short-circuit strength and well-defined negative-sequence behavior [3].

Negative-sequence-based protection elements, including Negative Sequence Directional Torque (32Q), Negative Sequence Impedance angle, and Directional Negative Sequence Overcurrent (67Q), are widely deployed to detect unbalanced faults and ensure selectivity in transmission networks [4]. These elements rely on the amplitude and phase relationship of negative-sequence currents relative to voltages for directional decision-making. In SG-dominated systems, negative-sequence current typically leads negative-sequence voltage by approximately 90°–100°, enabling reliable discrimination between forward and reverse faults [4]. However, IBRs often inject minimal negative-sequence current or exhibit phase angles that deviate significantly from conventional patterns due to converter control strategies, such as coupled sequence control or grid code compliance [5]. The implications of these changes are profound for transmission-level protection coordination. Misoperation of directional elements can result in unnecessary isolation of healthy lines or failure to trip faulted lines, jeopardizing system reliability and safety. Furthermore, the variability in IBR control strategies—such as coupled versus decoupled sequence control, fault ride through (FRT) behavior—adds complexity to protection setting calculations [6]. Therefore, understanding the interaction between grid code requirements and protection algorithms is critical for developing schemes that maintain dependability in high-IBR networks.

This paper addresses these challenges by analyzing the impact of German Grid Code, specifically the VDE-AR-N 4120 requirements [5] on negative-sequence-based directional protection in systems with significant IBR penetration. Through detailed electromagnetic transient simulations using several fault cases, control parameters, and current limiting strategies, the study evaluates the performance and accuracy of conventional negative sequence based directional elements. Results highlight misoperation risks and compares cases of FRT with no FRT and its impact on protection reliability. The findings aim to guide utilities and manufacturers in revising protection philosophies for grids dominated by IBRs.

The paper is organized as follows: Section II details the GFM inverter model, VDE-AR-N 4120 fault ride-through implementation, and current priority schemes. Section III explains the principles of negative-sequence directional protection and differences among 32Q and 67Q implementations. Section IV presents EMT simulation results comparing IBR performance with and without VDE-compliant FRT and their impact on directional protection. Section V concludes with key findings and recommendations.

## II. INVERTER FAULT RIDE THROUGH AND THE VDE PROVISIONS

### *1) Inverter modeling*

The inverter under consideration is modeled as a generic Virtual Synchronous Machine (VSM) combined with a droop-based grid-forming control strategy [7], augmented with virtual impedance to enhance stability and mitigate circulating

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currents. The inverter is represented using an averaged model, which captures the fundamental dynamics of the system while neglecting high-frequency switching effects. The inverter control with FRT has been illustrated in *Figure 1*.

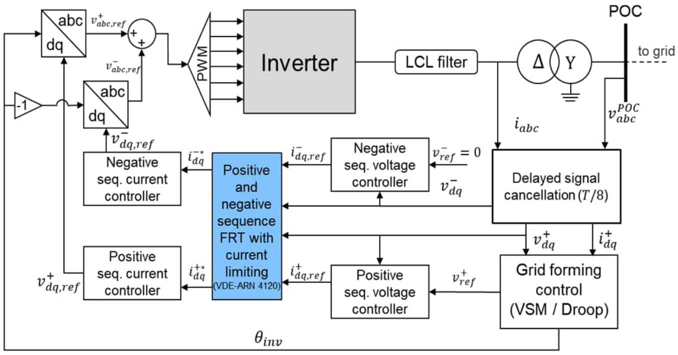
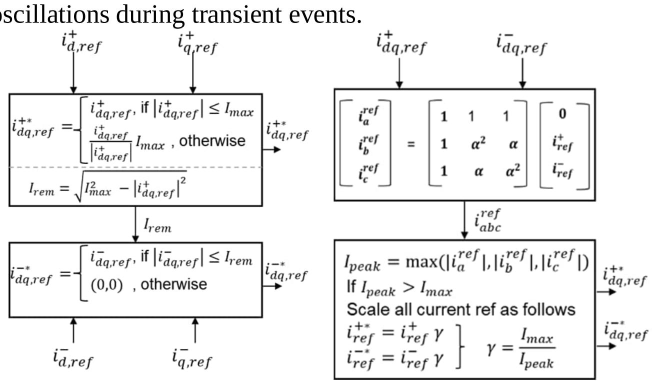



Figure 1: Inverter control block diagram with FRT

The inverter operates under a Decoupled Sequence Control framework, which enables independent regulation of positive- and negative-sequence components of voltages and currents. This approach is particularly advantageous in unbalanced or distorted grid conditions, as it allows selective compensation and improved dynamic performance. The control scheme, illustrated in *Figure 1*, involves extracting the sequence components from the measured three-phase quantities and applying separate control loops for each sequence.

To achieve accurate and fast sequence extraction, the Delayed Signal Cancellation (DSC) method described in [8] is employed. This method introduces a delay of $T/8$ (where $T$ is the fundamental period) to accelerate convergence of the extracted sequence components toward their true values. However, the inherent overshoot associated with this technique is mitigated through careful tuning of the proportional-integral (PI) controllers in the inner loops. This ensures a balance between dynamic response and stability, minimizing oscillations during transient events.




(a) Current priority scheme 1 (b) Current priority scheme 2

Figure 2: Sequence current priority and limiting - Scheme 1

We implement two sequence current limiting schemes shown in *Figure 2*. Scheme 1 prioritizes positive sequence current injection [9], allowing the remaining current capacity to be injected as negative sequence, if required. Scheme 2 shown in *Figure 2*(b) proportionally scales the positive and negative sequence current references, if any of the phase phasor magnitudes (computed from the positive and negative sequence reference phasors $i_{dq,ref}^{+/-}$) surpasses the maximum current, both of the references are scaled down proportionally.

*2) VDE ARN-4120 sequence current injection for VRT*

We will discuss briefly fault ride through with respect to the provisions of a widely adopted standard for inverter connection knows as the German VDE ARN-4120 standard. This standard overlaps with the IEEE 2800-2022 in certain specifications for voltage ride through, however offers more specific instructions on the sequence currents to be injected for dynamic grid support. In addition, the UNIFI (Universal Interoperability for Grid-forming Inverters) Consortium has released a document that seeks to provide uniform technical requirements for the interconnection, integration, and interoperability of GFM IBRs of any size in electric power systems [10].

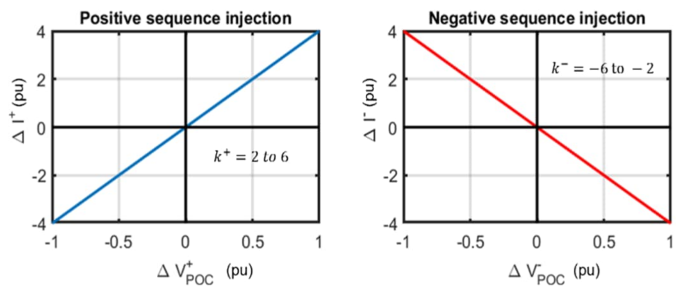



Figure 3: VDE ARN-4120 sequence current injection requirements

Figure 3 shows the VDE requirement for dynamic grid support during abnormal voltage conditions. The standard defined abnormal voltage as $V_{POC} > 1.1\ V_{nom}$ (high-voltage) or $V_{POC} < 0.9\ V_{nom}$ (low-voltage). This allows for the FRT mode to have a deadband to not activate on subtle changes in voltage due to load or slow system changes. $V_{POC}$ is the point of connection voltage, and $V_{nom}$ is the nominal/target bus voltage at the POC.

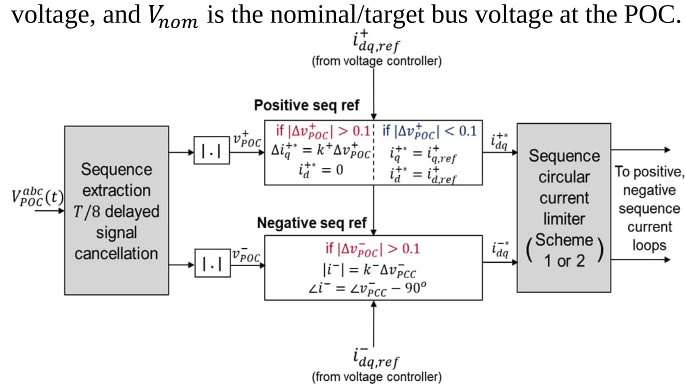



Figure 4: VDE ARN-4120 compliant fault ride through

Figure 4 shows our implementation of the FRT prescribed by VDE ARN-4120. During low voltage condition, we design the control to not inject any positive sequence real current $i_d^+$ and only inject reactive current $i_q^+$ according to Figure 3. For negative sequence, we inject the negative sequence current $i^-$ leading the negative sequence voltage at the point of connection (POC). While the VDE grid code does not explicitly dictate an angle, it does prioritize negative sequence reactive current support, as per the publicly available 2017 document. Therefore, we choose the $I_2$ to lead the $V_2$ by $90^o$. This ensures that all negative sequence current is used to minimize the negative sequence voltage magnitude $V_{2,POC}$ at the POC.

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## III. NEGATIVE SEQUENCE BASED DIRECTIONAL PROTECTION

Negative-sequence–based directional protection exploits the asymmetrical components that arise only during unbalanced conditions (single-line-to-ground, line-to-line, and double-line-to-ground faults). By forming negative-sequence phasors for voltage $V_2$ and current $I_2$, the directional element becomes inherently immune to balanced load flow and most power swings, which are predominantly positive-sequence. Direction is determined from the negative-sequence power flow—implemented in modern relays via a torque or operate quantity using the computed negative sequence voltage and current phasors. Depending on the direction of the operating torque, the direction is determined as a forward or reverse fault. Since this torque calculation and hence the correct directionality detection depends on both the magnitude and phase of the negative sequence current $I_2$, it can be impacted when the conventional synchronous machine source is replaced by IBRs. In practice, negative-sequence directional elements are paired with phase or ground distance/overcurrent units to supervise tripping and enable selectivity on complex networks with infeed from both ends.

We consider three types of negative sequence based directional protection schemes in this paper, namely – 32Q, negative sequence impedance angle-based, and 67Q. The first one is a negative sequence torque-based scheme $T_{32Q}$ [11], wherein the torque is calculated as

$$T_{32Q} = |V_2|\,|I_2| \cos\left(\pi - \angle Z_2^{line} + \angle V_2 - \angle I_2\right), \qquad (1)$$

where $\angle$ denotes angle of the phasor, and $Z_2^{line}$ is the negative sequence line impedance. Typically, if $T_{32Q} > \tau_{fwd}$, a forward fault is asserted, and if $T_{32Q} < -\tau_{rev}$, then a reverse fault is asserted. $\tau_{fwd/rev} > 0$ are thresholds for the relay to not trip for minor imbalances in the network due to loads.

The next type we consider is the negative sequence impedance based directional element. Here, the negative sequence impedance phasor is first calculated as $Z_2 = \frac{V_2}{I_2}$.

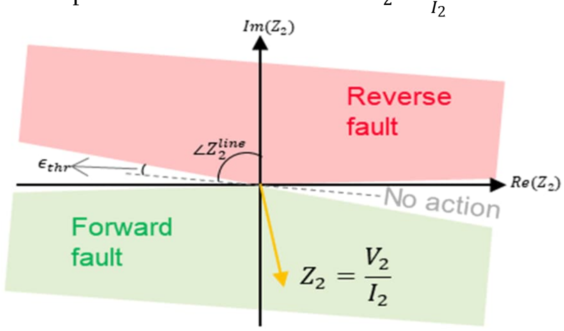



Figure 5: Negative sequence impedance plane

Figure 5 shows a typical negative sequence impedance plane for the impedance based directional protection. As can be seen, broadly speaking, if the negative sequence impedance phasor lies in the green area, it's declared a forward fault, else a reverse fault. Note, typically a small "no action" area is reserved as a safety, to ensure that incorrect directionality is not asserted at border cases. The last protection scheme that we investigate is the directional negative sequence overcurrent protection – 67Q. It uses the negative sequence current magnitude in addition to the measured negative sequence impedance angle to ascertain directionality and trip signals. Therefore, it only sends a trip signal for the desired direction when the negative sequence current magnitude is above a threshold $I_{pickup} > 0$, typically between 0.08-0.2pu. In this paper, we will use a threshold of 0.15pu. In the next section, we present numerical results with and without VDE ARN-4120 compliant FRT on the impact to the directional protection schemes described in this section.

## IV. NUMERICAL RESULTS

This section presents simulation results assessing the impact of IBR penetration on directional protection. In particular, we study the impact of IBRs having VDE compliant FRT compared to ones with no FRT on the accuracy of the directional protection schemes discussed in the previous section.

### 1) *Simulink test system*

The test system is a simple system shown in Figure 6, wherein the grid is modeled as a voltage source behind an equivalent impedance. The inverter is feeding power to the grid through a 33kV, 30km line in the VSM model. We focus on the relay R1 in this case to evaluate its directionality detection accuracy. We consider three types of unbalanced faults – a single line to ground (LG), a double-line (LL), and a double-line to ground (LLG) faults. These three variations capture the different intensities and types of unbalanced faults. The GFM inverter operates in VSM mode, feeding power radially into a grid modeled as a voltage source behind impedance. A Delta-Y ground transformer connects Bus-1 to the point of connection, with relay R1 placed on the Y-side of TF1 to monitor faults.

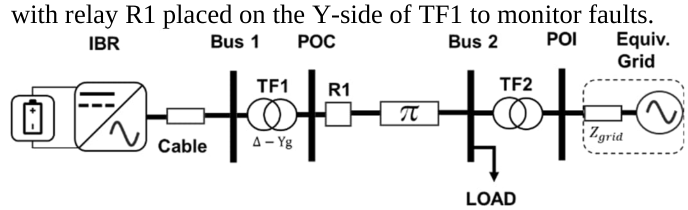
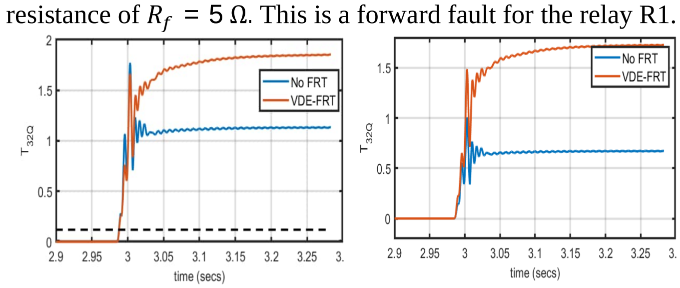



Figure 6: Test system – Simulink

The line is modeled as a pi-equivalent line with both positive and zero sequence data. The system MVA is 45MVA. The X/R ratio of the grid is chosen to be 5, with a short circuit ratio (SCR) at point of interconnection (POI) as SCR = 4.

### 2) *Single line to ground (LG) faults*

In this first test, we do a LG fault mid-line on line-1, with a fault resistance of $R_f = 5\,\Omega$. This is a forward fault for the relay R1.




(a) LG fault $R_f = 5\Omega$ (b) LG fault $R_f = 20\Omega$

Figure 7: Comparison of $T_{32Q}$ for LG midline fault

From Figure 7(a), we see that in both cases with and without FRT, the relay correctly detects it as a forward fault since the value of the torque $T_{32Q}$ is positive. However, in the case of VDE-compliant FRT with $k^+ = k^- = 4$, the torque is

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substantially larger compared to the case with no FRT. In this case, both current priority schemes showed similar results, since the inverter did not hit its current limit.

Figure 7(b) shows the case for a SLG fault with a higher fault resistance of 20Ω. In this case, similar to the lower fault resistance test, both control with and without FRT correctly detect a forward fault, with a higher torque value for FRT case.

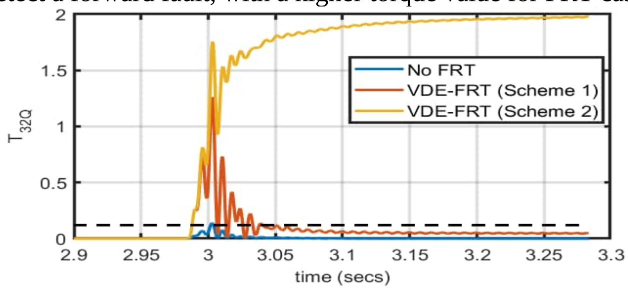
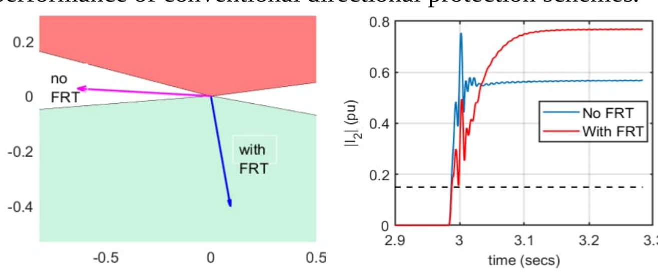


Figure 8: Comparison of $T_{32Q}$ for closein fault $R_f = 5\Omega$

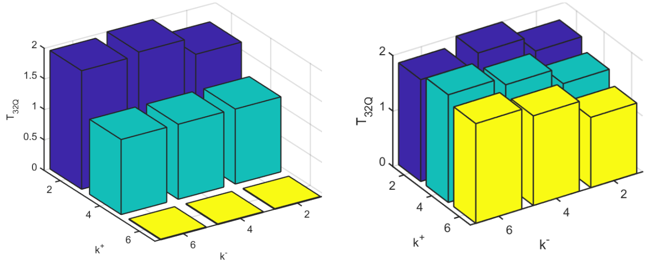
Next, we apply an LG fault with $R_f = 5\,\Omega$ at 1%-line length, a close-in fault to relay R1. In Figure 8, we can see that due to the fault being close to the POC, the positive sequence voltage sag is large. Due to this, both the no FRT case and current priority scheme-1 do not produce enough torque to declare a forward fault, due to negligible $I_2$ being dispensed. However, the priority scheme-2 is able to dispense sufficient negative sequence currents to have enough 32Q torque magnitude for a forward fault. This demonstrates that not only the grid code, but also implementation of sequence current priority impacts the performance of conventional directional protection schemes.



(a) Comparison of $Z_2$ angle (b) Comparison of $|I_2|$

Figure 9: Negative sequence quantities for 67Q, close-in fault

In Figure 9, we present the results for the negative sequence impedance angle and the current magnitudes for a mid-line fault. We can see that while the current magnitudes are sufficiently above the pickup value, the impedance angle with no FRT lies in the no action zone, with an angle of $176^o$. In the FRT case, as expected, the angle is $-82^o$, which enables correct detection of a forward fault.



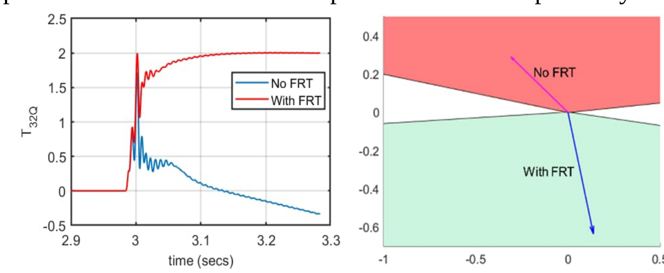
(a) Current priority scheme 1 (b) Current priority scheme 2

Figure 10: 32Q torque values for varying k(Scheme 1 vs Scheme 2)

Figure 10 shows the 32Q torque values for varying values of $k^{+/-}$ for two different priority schemes. From Figure 10(a), we can see that for scheme 1, for a very large value of $k^+$, a negligible value of $T_{32Q}$ is produced, hence not detecting a forward fault. The value of 32Q increases with decreasing $k^+$ and increasing $k^-$. On the other hand, for scheme 2 shown in Figure 10(b), the $T_{32Q}$ values are above threshold for all values of $k^{+/-}$, hence correctly detecting a forward fault. This shows that depending on what current limiting strategy is implemented by the vendor, and the gains set for the FRT current injections, 32Q might not be able to detect directionality.

*3) Line to Line (LL) faults*

Next, we test the performance of the directional protection for double line faults. We choose a fault resistance $R_f = 5\,\Omega$, and perform a midline fault on the phases A and B respectively.



(a) 32Q torque comparison (b) $Z_2$ impedance phasor

Figure 11: Performance comparison of LL fault with $R_f = 5\,\Omega$, midline fault

In Figure 11(a) we present the comparison of both the 32Q torque and the impedance angle. Unlike the LG fault scenario, the 32Q torque behavior here is notably different. In the no-FRT case, the torque transitions from positive to negative, with the initial positive value averaging around 0.33 pu—close to the directional threshold of 0.125 pu. This variability means the 32Q element may detect either a forward or reverse fault depending on the delay configured for directional determination. In contrast, with FRT enabled, the 32Q torque exhibits a stable and significantly positive trajectory, maintaining a value of approximately 2.0 pu, clearly indicating a forward fault. It is important to note that a 3–4 cycle window is typically required for IBR current settling post-fault, which should be considered in protection timing settings

Figure 11(b) shows the negative sequence impedance phasor or the impedance plane. In this case, unlike the LG fault case, the $Z_2$ phasor for the case with no FRT moves into the reverse fault region, hence wrongly indicating a forward fault as a reverse fault. The negative sequence current magnitude for the no FRT case was observed to be $I_2^{noFRT} = 0.67$pu, which is larger than the pickup current of 0.15pu, hence allowing the relay to incorrectly declare a reverse fault. However, in the case with FRT, the negative sequence impedance angle lies in the forward fault region with an angle of $-78^o$, with a current magnitude of $I_2^{FRT} = 0.61$pu. This proves that with FRT, both the negative sequence angle and the current magnitudes remain consistent and reliable for LL faults for conventional directional protection to operate.

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*4) Double line to ground (LLG faults)*

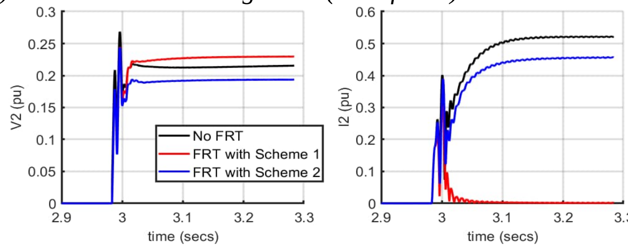
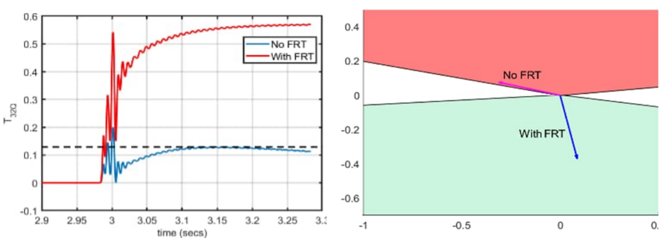


Figure 12: Comparison of negative sequence voltage and current magnitude for LLG fault with $R_f = 15\,\Omega$

Figure 12 shows the comparison of the negative sequence current injections and the negative sequence POC voltage for the case with no FRT, FRT with current priority scheme 1 and scheme 2. We can see that due to the LLG fault causing a large positive sequence voltage sag, and $k^+ = 4$, with current priority scheme 1, all the current capacity is used to inject positive sequence current. Hence, as shown in Figure 12, no negative sequence current is injected, causing the largest negative sequence voltage magnitude for that case. With scheme 2, even though a smaller $I_2$ is dispensed compared to the case with no FRT, however, a lower negative sequence POC voltage is observed. Since no negative sequence current is injected with scheme 1, the directional relays will fail to operate, hence we will only compare scheme 2 in more detail.



(a) 32Q torque for LLG fault (b) Impedance phasor for LLG

Figure 13: Comparison of FRT and no FRT for LLG faults

Figure 13 shows the comparison of the no FRT case with FRT having current priority scheme 2. From Figure 13(a), we can see that the 32Q torque for the case with no FRT touches the threshold, but never crosses it, hence absolutely failing to make a decision on the directionality of the LLG fault. However, the case with FRT has a value of $T_{32Q} = 0.574$, which is more than the threshold value. This allows the 32Q protection element to correctly operate for LLG faults. In Figure 13(b), we show the impedance phasor for both cases. Similar to the LL fault scenario, we see that the case with no FRT incorrectly declares a forward fault as a reverse fault, as indicated by the $Z_2$ phasor having an angle of $159^o$ causing incorrect action by negative sequence impedance angle-based and 67Q elements. With FRT enabled, the issue is not present, and the negative sequence impedance angle is $-81.5^o$.

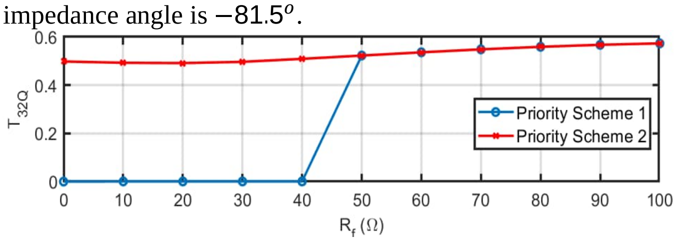


Figure 14: Comparison of 32Q : FRT with Priority Schemes 1 and 2

*Figure 14* shows the comparison of the 32Q torque for FRT with current priority schemes 1 and 2 during a LLG fault. We can see that for higher fault resistances, both schemes perform identically for same value of $k^{+/-}$. However, at lower fault resistances, when the positive sequence voltage sag is larger, the scheme 2 performs better, and provides a larger value of forward torque at all fault resistances, staying above the operating threshold of 0.125pu. This is because scheme 2 proportionally reduces the sequence currents.

## V. Conclusion

We investigated the influence of the German grid code VDE-AR-N 4120 on negative-sequence-based directional protection schemes in systems with GFM IBRs. The analysis focuses on scenarios with and without fault ride-through compliance. We demonstrated that non-compliance with FRT requirements significantly compromises directional accuracy due to insufficient negative-sequence current injections and altered phase relationships. Conversely, VDE-compliant FRT improves directional integrity by enforcing reactive current injections proportional to negative-sequence voltage. The choice of proportional sequence current priority versus positive-sequence priority has a critical impact on protection reliability. Lastly, we show that variations in grid code implementation, such as current-limiting strategies, can further affect the dependability of negative-sequence directional elements, highlighting the need for adaptive protection in IBR dominated grids.


Disclaimer: The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.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