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Impact of Inverter-Based Resources on Grid Protection: A Review of Negative-Sequence Current Generation

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Xue Lyu (PNNL)
Jing Xie (PNNL)
Thomas E McDermott (Meltran, Inc.)

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Pacific Northwest National Laboratory
Richland, Washington 99352

Contents

Abstract

The increasing integration of inverter-based resources (IBRs) in power grids poses challenges to traditional protection systems, primarily due to their different fault current signatures compared to conventional synchronous generators. Unlike synchronous generators whose fault response is dictated by their physical design, IBRs exhibit a wide range of fault characteristics due to manufacturer-specific control algorithms and settings. This dependence on proprietary control schemes complicates the modeling of IBR behavior during faults significantly. The complication increases further, with respect to the rapid evolution of inverter technology and the diverse control strategies employed.

While much research has focused on the positive-sequence current injections of IBRs during symmetrical faults, the understanding of negative-sequence current generation during non-symmetrical faults remains limited. This report provides a brief overview of research on IBRs' negative-sequence current generation during unbalanced faults and its impact on protection schemes based on negative-sequence components. Both Type III wind turbines and full-size converter-based IBRs are covered. Furthermore, strategies for grid-forming and grid-following controlled inverters to generate negative-sequence currents during unbalanced faults are reviewed.

1.0 Introduction

The global share of renewable energy sources, such as wind turbines (WTs) and photovoltaic (PV) cells, continues to increase, driven by technological advancements and declining costs. The solar plants, Type III WTs (i.e., doubly-fed induction generator (DFIG) based WTs), and Type IV WTs (i.e., full rated power converter-based WTs) are connected to grids via power electronic inverters. The increasing penetration of IBRs impacts legacy power system protection schemes, as they have different dynamic and transient behavior compared to conventional synchronous generators (SGs).

The typical fault characteristics of IBRs, reported in [1], include: (1) The sustained fault current magnitude from PV systems and WTs is typically low due to inverter current limitation. (2) IBR fault currents usually exhibit an initial transient response lasting between 0.5 cycles to 1.5 cycles, after which they are limited to the allowable limits of the inverter. (3) The angular between the voltage and current during the fault is determined by the IBR's control strategy. (4) IBR fault currents typically lack a zero-sequence component, and negative-sequence current is often partially or fully suppressed depending on the control algorithm. Consequently, protection systems designed for SG-dominated power systems may not function properly under conditions with high penetration of IBRs.

The focus of this report is on reviewing the impact of IBRs on protection schemes relying on negative-sequence quantities. It should be noted that even though Type III WTs, Type IV WTs, and solar PV systems are all IBRs, their grid interconnection structures are different. Type IV WTs and solar PV systems are connected to grid via a full-size converter with respect to their total power generation. In contrast, the stator of a Type III WT is directly connected to the grid, while the rotor is connected via a converter. The size of the converter of the Type III WT is typically around 30% of the total generation. As a result, the negative-sequence current response of full converter-based IBRs and Type III WTs becomes different.

The current injection of full converter-based IBRs during faults is entirely determined by their control scheme. Two categories of control schemes are typically utilized: the coupled sequence control (CSC) scheme and the decoupled sequence control (DSC) scheme. Under the CSC scheme, the negative-sequence current is not directly regulated by the control system and the converter is not anticipated to generate any negative-sequence currents into the grid during unbalanced loading conditions or faults. This absence of negative-sequence fault current contribution from IBRs may lead to protection system misoperation. On the other hand, the DSC control scheme enables independent control of both positive-sequence and negative-sequence currents, reducing the possibility of protection system misoperation.

For Type III WTs, their induction generator rotor circuits provide a low impedance path to the negative-sequence currents under unbalanced faults. Therefore, their unbalanced fault behavior is similar to SGs under traditional CSC. The DSC scheme can also be employed at the rotor-side converter (RSC) or grid-side converter (GSC) of Type III WTs to further regulate the negative-sequence current generation.

Grid codes start to require negative-sequence current injection from IBRs. For instance, German standards VDE-AR-N 4120 [2] and VDE-AR-N 4130 [3] require that the negative-sequence current injected by an IBR have an amplitude proportional to the negative-sequence terminal voltage, with a characteristic proportional gain k typically ranging between 2 and 6. The recently approved North America IEEE Standard 2800-2022 [4] requires IBRs to generate negative-sequence reactive current during unbalanced low voltage conditions. This negative-current should lead the negative-sequence voltage by 90° to 100° for full converter-based IBR units and 90° to 150° for Type III WTs. In addition, the magnitude should be dependent on IBR unit terminal negative-sequence voltage. While IEEE 2800-2022 was initially designed for conventional grid-following (GFL) IBRs, it applies to all IBRs, including those employing grid-forming (GFM) control. Given that GFM is a relatively new technology, new control strategies are required to generate the necessary negative-sequence current under unbalanced faults. Recently, some studies have proposed control strategies that can independently regulate the positive- and negative-sequence currents from the GFM-controlled inverters. Detailed information on these strategies will be discussed in Section 3.

This report summarizes current findings regarding the impact of different types of IBRs with different kinds of controls on negative-sequence protection schemes in the following sections. Section 2 investigates the negative-sequence current response of IBRs utilizing GFL control, including Type III WTs and full converter-based IBRs. Section 3 focuses on the negative-sequence current generation of GFM-controlled inverters. Section 4 provides the conclusion.

2.0 Inverter-Based Resources with Gird-Following Control

Most IBRs deployed in power grids utilize the GFL control. They are considered a current source, using a phase-locked loop (PLL) to track the voltage at the point of common coupling (PCC). A specified amount of active and reactive power is injected into the PCC. GFL control is effective when IBRs are connected to a sufficiently robust AC power system, where minimal voltage variation occurs at their terminals in response to changes in currents injected by IBRs. As the negative-sequence response of Type III WTs and full converter-based IBRs are different, they are discussed separately in this section.

2.1 Type III Wind Turbines

When DFIG WTs adopt the conventional coupled sequence control, their unbalanced fault behavior is similar to SGs as the induction generator rotor circuits provide a low impedance path to negative-sequence currents. According to the simulation results outlined in [5], traditional CSC shows the effectiveness of the over-current relay operation. This is attributed to the fault-induced negative-sequence current from Type III WTs exceeding the predefined negative sequence pick-up current threshold of the instantaneous negative-sequence over-current 50Q. Additionally, the directional negative-sequence over-current protection 67Q element relay proves successful in Type III WTs, attributed to the leading nature of the apparent negative-sequence voltage compared to the negative-sequence current. Although mis-operation was not observed in simulation of [5], field measurements suggest the potential for such occurrences.

In [6], several methods are compared, including: 1) the classical balanced positive-sequence control (BPSC); 2) a positive- and negative-sequence control focusing on electromagnetic torque (PNSG-Tem) [7] (which generates negative-sequence current through the RSC to eliminate double grid frequency oscillations in electromagnetic torque); 3) a coordinated control that uses GSC to provide negative-sequence current [8]; and 4) a flexible control of the reactive current in the positive- and negative-sequence system (PNSC-I12R) to comply with positive-sequence current and negative-sequence current requirements in emerging grid codes. Mathematical analysis and simulations indicate that BPSC, PNSG-Tem, and the coordinated current control do not meet the requirements for negative-sequence current from wind farms during severe voltage unbalance caused by asymmetrical faults. The PNSC-I12R is indicated as capable to address the shortcomings of those control schemes.

According to [9], the deviation of a DFIG's negative-sequence current and voltage from its ideal $[90°, 100°]$ range during low-voltage ride-through (LVRT) under CSC deviates from standard behavior. This deviation is primarily influenced by the bandwidth of the RSC's current control loop. This deviation can adversely affect the relays, even if the negative-sequence current angle of a DFIG falls within the range of $[90°, 150°]$, as allowed by the IEEE 2800-2022 for Type III WTs. When a DFIG uses dual current control for the RSC to suppress electromagnetic torque pulsations, the angle may fall outside of the $[90°, 150°]$ range. To address this issue, a new dual current control scheme for GSC is proposed in [9]. This scheme ensures that the angle of the point of connection's negative-sequence current leads the respective voltage by an amount between $90°$ and $100°$. It may eliminate the necessity for a specific negative-sequence current generation requirement for Type III WTs in future revisions of the IEEE 2800-2022.

2.2 Full Converter-Based IBRs

In a Type IV WT using traditional coupled sequence control [5], the 50Q protection fails to trip because the amplitude of the negative-sequence current is insufficient. The 67Q protection fails to detect the fault direction because changed phase angle of the negative-sequence current and voltage phasors. Additionally, fault identification fails to identify the faulted phase, as the negative-sequence current leads the zero-sequence current by $80°$, which falls outside any fault identification sector. According to [5], the number of WTs in operation could also influence both the amplitude and phase angle of the negative-sequence fault current, thereby impacting the performance of both 50Q/51Q and 67Q.

In accordance with the German grid code VDE-AR-N 4120, [10] implements a negative-sequence current control on a Type IV WT. This decoupled sequence control scheme is integrated with the grid-side converter control to calculate the current set-point for achieving the desired negative-sequence current characteristic. Detailed information can be found in [11]. The study finds that the proportional gain k, which determines the amplitude of the injected negative-sequence current, cannot be increased arbitrarily due to the inverter current limit. Moreover, [10] reports that in the absence of individual limits on $d-$axis and $q-$axis currents I_d and I_q, the injected negative-sequence current may not primarily be inductive. The performance of negative-sequence quantity-based protection schemes for Type IV incorporating VDE-AR-N 4120 is evaluated in [10]. Simulation results demonstrate that the mis-operation of instantaneous negative-sequence over-current 50Q is resolved with the negative-sequence current control, owing to the increased level of negative-sequence current. Note that there is a time delay in the operation of 50Q due to the rise time of the negative-sequence current. Additionally, the mis-operation of directional negative-sequence over-current 67Q is resolved due to the enforced angular relationship between negative-sequence voltage and current of the WTs. Under VDE-AR-N 4120, incorrect fault identification is also addressed by this enforced angular relationship.

Precise tracking of the negative-sequence phase angle is essential for implementing decoupled sequence control. As emphasized in [12], the negative-sequence phase angle typically differs from the positive-sequence phase angle. There is a steady-state phase-angle difference between them. A decoupled double synchronous reference frame PLL (DDSRF-PLL) is used in [13] for tracking negative sequence current. It employs a decoupling network to isolate the positive-sequence signal from the negative-sequence signal. [12] utilizes three different PLLs, one for each phase abc, to track the negative-sequence phase angle.

An enhanced dual current control scheme is proposed in [14] to regulate the relative angles of the IBRs sequence currents during unbalanced faults to enable accurate identification of the fault type by the existing phase selection methods (PSMs). The proposed control in [14] comprises three stages. Firstly, the fault type is identified using the sequence voltage at the terminal of IBRs. Secondly, negative-sequence current is generated to mimic the characteristics of SG sequence current during unbalanced faults. Finally, the sequence currents of IBRs are controlled in the double synchronous reference frame to track the reference angle. Various fault and relay locations, fault resistances, and grid code requirements from Spain, Germany, and North America are taken into account to assess the reliable operation of angle-based PSMs, when IBRs use the proposed dual current control scheme. Another dual current control scheme is proposed in [15], where the IBR is controlled as a voltage source behind an adaptive virtual impedance in the positive-sequence circuit. In the negative-sequence circuit during faults, the inverter functions as a single virtual impedance. Objective of the control scheme in [15] is to ensure the proper operation of the directional, phase-selection, and distance elements of a relay.

In [16], a phasor-domain modeling approach for wind farms with Type IV WTs is introduced. This model incorporates fault ride-through functionality and offers the option of decoupled sequence control in the GSC. For solar PV, similar control strategies can be utilized. As a result, the findings and conclusions drawn from Type IV WTs are applicable to solar PV systems as well.

3.0 Inverter-Based Resources with Gird-Forming Control

While IBRs predominantly employ GFL control strategies, GFM control is emerging as a future trend due to its ability to regulate the terminal voltage and maintain system stability. Since GFM-controlled IBRs function as voltage sources behind impedance, their current injection is greatly influenced by electrical network conditions. While SGs can provide several times their rated current, GFM-controlled inverters cannot. Therefore, during grid faults, the current limiting strategies of GFM-controlled inverters are important for protecting themselves. Recent studies have explored methods (e.g., current saturation and virtual impedance) to limit currents during voltage faults, primarily focusing on balanced faults and positive-sequence current limiting. To meet the negative-sequence current injection requirement of grid codes, separate current-limiting schemes for each sequence circuit are necessary during asymmetrical LVRT events.

In [17], a sequence-based control technique is proposed for both grid-forming and grid-following interfaced distributed generators. The positive-sequence and negative-sequence components are separated in synchronous reference frame for the grid-forming inverter. A current limiting block is designed to transform the positive- and negative-sequence reference currents in synchronous reference frame to natural reference frame to calculate the current magnitude. Then, it determines the current saturation reference. Finally, the limited reference currents in the natural reference frame are transformed back into their counterparts in the synchronous reference frame and passed through PI current controllers to complete the control process. As a result, the inverter currents can be constrained to a predefined threshold for both balanced and unbalanced faults.

The LVRT capability of droop controlled GFM PV sources is explored in [18]. This work utilizes a second-order generalized integrator to separate the measured voltage and current at the PV source output terminals into positive- and negative-sequence components. Alongside the main control that regulates the positive-sequence components, it incorporates negative-sequence current compensation into the modulation index generation to mitigate PV DC-bus oscillations induced by double-grid-frequency oscillations of power during unbalanced grid faults. In [19], per-phase phasor models of both GFL and GFM inverters are introduced for supporting dynamic studies in a distribution system with unbalanced construction.

Furthermore, a control scheme proposed in [20] aims to ensure that GFM IBRs comply with the negative-sequence current requirements specified in IEEE 2800-2022. The GFM inverter is controlled to function as a voltage source behind an impedance in the positive-sequence circuit. However, the negative-sequence circuit is controlled as a current source to produce the desired magnitude and angle for the negative-sequence current at its terminal. An adaptive sequence current division scheme proposed in [20] allocates the inverter's current generation capacity between positive- and negative-sequence currents, maximizing utilization under all conditions without the need to identify faulty phasor(s). An adaptive virtual impedance method is utilized to ensure that its positive-sequence current remains within the maximum limit during steady state, while also ensuring compliance with the requirement for negative-sequence current generation. An edge-triggered pulse generator with a predefined duration is utilized to prevent the positive-sequence current from exceeding its maximum during initial transients. A current saturator is implemented to restrict the negative-sequence current to its maximum throughout the duration of the fault. Simulation results confirm the compliance of this control with IEEE 2800-2022.

Overall, the research on controlling the generation of negative-sequence current from GFM inverters and its impact on protection schemes is still in its early stages and requires further research.

4.0 Conclusion

The synchronous machine-based system is considered as a voltage source behind an impedance. Fault currents in SGs are impacted by the impedance between the source and the fault point. Regardless of the size, manufacturer, or type of energy source, the fault behavior remains consistent. The magnitude and angular relationship between fault current and voltage are predictable, which forms the basis for designing protection schemes tailored to SG characteristics.

In contrast, the response of IBRs largely depends on the control schemes of the converter. Currently, the generation of negative-sequence current by IBRs during unbalanced conditions lacks consistency and varies among different types of IBRs. The Type III WTs can naturally include a negative-sequence current component under the conventional vector control. However, full converter-based IBRs require an additional negative-sequence current controller to comply with grid code requirements. Differences in the control schemes of IBRs contribute to variations in the performance of negative-sequence current generation.

Despite the requirements outlined in IEEE 2800-2022 for IBRs connected to transmission power systems regarding negative-sequence current generation, conducting detailed electromagnetic transients (EMT) studies is crucial for a comprehensive understanding of IBRs' responses to negative-sequence currents. Moreover, further research and standards are needed to ensure the proper coordination between relays and IBRs' control systems, ensuring the correct operation of protection systems.

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