

IBR Fault Response Reimagined: Supporting Traditional Protection Principles and Protection Engineering Practices

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IBR Fault Response Reimagined: Supporting Traditional Protection Principles and Protection Engineering Practices

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SUMMARY

This paper proposes a simple method for protection-friendly fault response from inverter-based resources (IBRs) in high-voltage networks. Protection engineering continues to rely on IBR models and simulations, which are costly, fragile, and sensitive to changes in IBR controls. Existing standards, such as IEEE 2800, focus on phasor-based performance and allow delayed IBR response to fault conditions, leaving the performance during the first cycles of a fault insufficiently defined from the protection perspective. The paper notes that transmission faults are short, typically clearing within a few cycles, and that control-driven IBR response is ineffective over such time frames. Control actions have a time lag and distort the natural relationship between voltages and currents, leading to degradation of protection performance. IBR fault response should, instead, be instantaneous and aligned with traditional power system behavior, namely a high-inertia source behind an inductance.

Based on these principles, the paper proposes a method in which IBR currents follow terminal voltages through a fixed linear RL branch. The resulting response is instantaneous and preserves the voltage-current relationships relied on by protective relays for more than a century. The method prohibits fast control loops during faults and enables simple and robust modeling of IBRs as current sources behind fixed impedances.

KEYWORDS

Fault Response, Inverter-Based Resources, Protective Relaying, Short-Circuit Modeling, Virtual Shunt Reactor, Voltage-Current Consistency.

1 Introduction

The fault response of inverter-based resources (IBRs) remains one of the most pressing challenges in modern power systems and a key focus of ongoing standardization efforts. Despite years of work, progress has been limited, and protection engineers continue to face uncertainty regarding IBR behavior during faults. Design of protection systems for applications near IBRs continues to rely on detailed modeling and simulations. However, this approach is fragile and not economical: changes in IBR control algorithms (such as firmware updates) or user-adjustable settings can invalidate prior studies and necessitate costly re-engineering. Although model-based protection engineering was initially unavoidable, it is not a sustainable long-term solution.

The effort to standardize the IBR fault response has fallen short because there were no established practices or methods available to serve as candidates for a standard. New methods had to be rushed as part of the standardization process itself. Historically, the protection community focused on protecting apparatuses rather than shaping their behavior, which delayed recognition of the need for harmonized IBR fault response requirements. Current standards, such as IEEE Std 2800 [1], specify phasor-based performance and allow generous fault response times. As a result, IBR fault response during the critical first few power cycles remains problematic, precisely when protective relays must operate.

IBR technology continues to evolve with the introduction of grid-forming inverters (GFM). Compared with grid-following inverters, GFMs provide substantially greater control capabilities. As a result, more control functions can influence the IBR output during fault conditions, and more control parameters may affect the IBR fault response. These added complexities further complicate the effort to achieve protection-friendly IBR fault response.

This paper proposes a new way of thinking about the IBR fault response in high-voltage networks. Our method is simple, grounded in first principles, and implemented in the time domain. It prioritizes speed, signal consistency between fault voltages and currents, and sequence network homogeneity. The method avoids using control-based shaping of fault currents and instead employs a virtual shunt reactor that allows IBR currents to follow the IBR voltages just like in the case of any other element in a power grid. This method offers several benefits: it supports traditional protective relaying principles, removes the need for extensive modeling when setting instantaneous protection, and enables protection innovation by ensuring persistent voltage-current relationships during faults. Importantly, it achieves these goals without adding any significant cost or complexity for IBR manufacturers.

By constraining IBR fault response rather than expanding it, the method provides a clear path for standardization, improving protection reliability and reducing the protection engineering effort, time, and cost in networks with high IBR penetration.

2 IBR Fault Response Constraints and Opportunities

It is essential to recognize the fundamental constraints and opportunities of the IBR fault response and use them as the starting point for a realistic and practical solution.

2.1 Transmission Faults Clear in a Few Cycles

Transmission-grade protection differs greatly from distribution-grade protection. Carrying over IBR practices originally developed for distributed energy resources (DERs) is unnecessary and significantly limits what we can achieve at the transmission level. In transmission networks, the relevant fault durations are about 3 or 4 cycles for normal clearing and about 11 or 12 cycles for breaker failure contingencies. Established protection methods achieve these clearing times, and we should rely on them and optimize the IBR response for these practical fault clearing times. We can treat longer fault duration strictly as a contingency.

2.2 IBR Control Actions Are Counterproductive for Brief Events

If an IBR responds with a control action to a fault, that action does not accomplish much. The typical time allowance for IBR control actions spans several cycles or more. By the time the control action settles or is about to settle, the fault has already cleared. As a result, the control action must then reverse. This sequence, a control action followed immediately by its reversal, does not help protective relays and may even harm system stability. From this perspective, the term “fault ride through” should be understood literally as the ability to ignore the fault by refraining from any control action under the assumption that the fault will normally clear in 3 to 4 cycles. By eliminating all fast control actions related to the IBR outputs, one removes the need to know and model, when engineering protection systems, the many controls present in modern IBRs. Transformer tap changer control logic is a traditional example. Tap changer control is time-coordinated against faults and tap changers do not add complexity to the short-circuit calculations and protection.

2.3 Shaping IBR Fault Currents Through Control Is Problematic

Control loops that respond to voltage phasors do not produce natural or instantaneous IBR fault currents. The inherent time lag in this approach causes the current to lag the voltage in time. This lag prevents relays from operating without intentional time delay and further complicates conditions when the fault evolves, for example, through changes in resistance or fault type that alter the voltage during the event. The voltage-current lag remains unavoidable if using phasors, and we cannot expect future technological progress to remove it. Phasor estimation takes time, and its associated delay will always exist. IBR fault-response standards of today effectively mandate behavior that is nonlinear, with dead bands and limiters, and a time lag. These characteristics alone alter the nature of the network and jeopardize protection, regardless of the specific control action used to shape the fault response.

2.4 Allowing Time for IBR Fault Response Is Problematic

Protective relays in transmission networks must receive favorable operating signals starting at the very beginning of the fault. Allowing the IBR ample time to produce the desired fault currents effectively imposes an intentional time delay on protective relays. In addition, because the standards do not constrain the initial IBR fault response, different IBRs may respond differently following the changes in the signal that drives the fault response, such as the negative-sequence voltage. An instantaneous IBR fault response is both desired and logical. All elements in the network respond instantaneously, and the IBRs should do the same.

2.5 IBRs Will Remain Current-Limited

Inverter semiconductor devices limit IBR phase currents to approximately 1.2 to 1.5 pu, with a possible future increase to about 2 pu. Cost pressures will continue to favor sizing semiconductor devices for load rather than for fault conditions, so these limits will persist even if higher-rated devices become available. As a result, expecting IBRs to deliver high fault currents is not justified or necessary. High fault currents pose greater danger and avoiding them should not be necessarily viewed as a limitation. At the same time, insisting that the IBR current limit is or will remain very low exacerbates the issue, prompting implementations that remove the active load current following fault inception to create headroom for more reactive current.

3 Realistic IBR Fault Response Attributes

When considered over the time frame of a fault cleared by transmission-grade protection systems, all traditional power system elements behave as fixed impedances or as high-inertia sources behind fixed impedances. The terms impedances and sources are used here as a simplification. A more accurate representation is a three-phase time-domain model described by linear RL differential equations. The ubiquity of high-inertia sources and fixed impedances leads to well-established relationships between voltages and currents during any sudden voltage changes, especially faults. These relationships form the basis of essentially all protection principles in use today.

To preserve compatibility with existing protection methods, new apparatuses introduced into the power system, particularly sources, should exhibit the expected voltage-current relationships implied by the fixed impedance and high-inertia source model. In addition, this behavior must be preserved in the time domain, without a time lag between voltages and currents. If the fault response of a source is governed primarily by arbitrary control actions that are not directly tied to system voltages, the resulting current response is likely to violate one or more protection principles. Removing the active load current at fault inception to create headroom for reactive fault current is a good example of such undesired control actions.

Following, we describe a realistic fault response using a language of phasors, symmetrical components and sequence networks, all within the context of the time domain. We use these complementary descriptions for ease of understanding. They all support the same conclusion, however; there is only one physically consistent and protection-compatible solution to the IBR fault response challenge: a high-inertia source behind a fixed RL branch.

Changes in currents, that is “fault currents,” must follow changes in voltages. This voltage-current relationship must be 1) instantaneous, with no time delay, 2) wideband, not limited to a single frequency, 3) preferably linear, represented by a fixed RL branch, and 4) applicable to all voltage-current pairs, not only the negative-sequence. These requirements, when expressed using phasors and impedances, result in a fixed negative-sequence impedance and a fixed positive-sequence source behind a fixed positive-sequence impedance. This model is fully compatible with established protective relaying assumptions and principles.

It is worth emphasizing that currents should follow any voltage changes, not only voltage collapse during faults. Consider switching events such as load pickup or rejection or switching a capacitor bank or a shunt reactor in or out of service. These events change voltage magnitude, phase, or both. Breaker pole discordance creates a temporary imbalance during switching. The

source should respond with current changes that are consistent with the voltage changes. A control-based fault response method does not perform well in these situations because it may wait for a significant voltage depression before initiating a current response.

Any current response that is not directly linked to voltage through a linear RL branch violates the assumptions on which protective relaying is based. Therefore, like in a synchronous generator (SG), the ideal positive-sequence source in the IBR model must behave as a high-inertia source. It must continue to output the pre-fault magnitude, angle, and frequency, while allowing voltage changes at the IBR terminals to superimpose fault currents that are proportional to and congruent with the voltages.

Any arbitrary control of the output currents that does not follow voltages through an RL branch will violate protection assumptions. As a result, if there is a need to control the IBR circuit to balance the power flow, prevent overvoltages across the dc capacitor, and for similar reasons, that control should be carried out on the input (dc) side and not on the output (ac) side. During fault conditions, the electric power system and the fault decide the changes in the ac signals and the IBR should not attempt to “fight” the fault but, instead, it should respond with current changes that are congruent with voltage changes.

The superimposed fault currents, when added to the pre-fault load current, must remain within the available IBR current headroom, such as 1.2 to 1.5 pu. Compliance with this constraint is achieved by selecting a sufficiently large impedance in the IBR model. Attempts to use nonlinear voltage-current relationships or to dynamically modulate the impedance introduce unusual current patterns and risk violating protective relaying assumptions and principles. If dynamic changes are applied, they must be sufficiently slow relative to the duration of a power cycle and will, therefore, manifest only during post-fault voltage recovery or during very slowly cleared faults.

Achieving a high-inertia response from an IBR is neither difficult nor impractical. Being current-limited and highly controllable, an IBR can sustain the ideal source response at the pre-fault frequency and the current magnitude and angle for the duration of a fault while tracking the system dynamics by using time constants selected to match the dynamics of SGs.

4 Deriving the IBR Fault Response Model and Parameters

Figure 1a shows a simplified positive- and negative-sequence model of an SG. The positive- and negative-sequence impedances are relatively constant (we use the transient direct-axis reactance when considering an SG fault response). The positive-sequence voltage source changes slowly because of flux continuity (electromagnetic force magnitude) and mechanical inertia (electromagnetic force magnitude phase and frequency). Slow changes in the source and the positive-sequence impedance occur in practice but are inconsequential for protection.

We use the Thevenin-Norton equivalent and express the circuit in *Figure 1a* by a current source, as shown in *Figure 1b*. As long as the parameters match between *Figure 1a* and *Figure 1b*, the current-based model in *Figure 1b* provides an identical fault response to the voltage-based model in *Figure 1a*. Of course, an IBR is current-limited, and therefore we cannot use the parameters as in *Figure 1b*. To obtain a practical IBR fault response while using the SG template, we need to adjust the parameters in the model, as shown in *Figure 1c*.

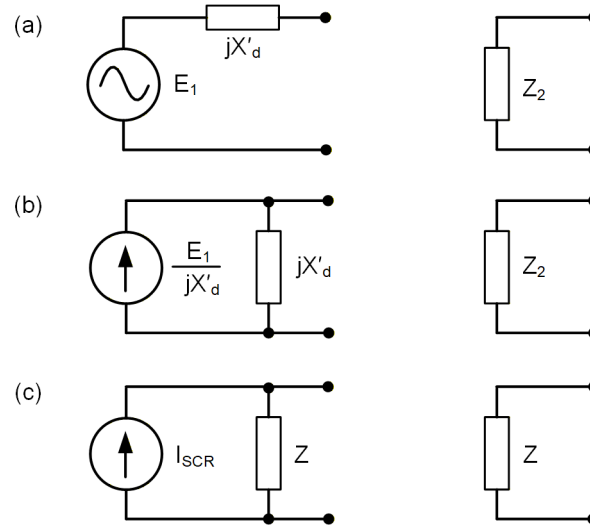


Figure 1 - SG Thevenin (a) and Norton (b) models; SG-inspired IBR model (c).

We select the parameters as follows.

4.1 Sequence Impedances Equality

We force the positive- and negative-sequence impedances to be identical (Z). Having these impedances equal simplifies the implementation. With the exception of rotating machines, all elements in a power system have their positive- and negative-sequence impedances identical, at least in theory. As a result, arbitrarily forcing the two impedances—that are not that different in an SG to begin with—to the same value (Z) makes the IBR more similar to the rest of the power system.

4.2 Impedances Angle Selection

We select the angle of the impedance (Z) to maximize homogeneity of the network. The positive- and negative-sequence equivalent networks in high-voltage systems have impedance angles of approximately 80–86 degrees. Therefore, we can use a fixed angle of 85 degrees and maintain high homogeneity of the network.

4.3 Impedance Magnitude Selection

We select the magnitude of the impedance (Z) to limit the current that flows in the shunt impedance so that the total current at the IBR terminals during faults does not exceed the maximum permitted level. The worst-case scenario to consider is a bolted fault at the IBR terminals (IBR fault). However, one can also use a bolted fault at the high-voltage side of the step-up transformer (system fault). When considering the worst-case system fault, one would select a lower impedance and allow slightly higher currents during faults, aiding relay sensitivity and dependability. Of course, during faults at the IBR terminals, the current would exceed the IBR limit, and this violation can be addressed by clipping the instantaneous current before passing it to the pulse-width modulator and inverter.

4.4 Current Source Behavior

The current source in the model must be a high-inertia source to retain proper operating conditions for protection. The source must continue at the pre-fault magnitude, angle, and frequency. The source does not have to be, nor should it be, perfectly static. It should follow the system with a time constant that is consistent with large SGs. We do not advocate “freezing”

the source in practical implementations. Note that the source is a controlled entity. It follows closed-loop controllers that determine the current that an IBR should output. We advocate that all such controllers have sufficiently long time constants so that they do not modulate the source too quickly.

5 Implementation

We can implement the SG-inspired IBR described in the previous section by using the concept of a shunt virtual reactor, as shown in **Figure 2**.

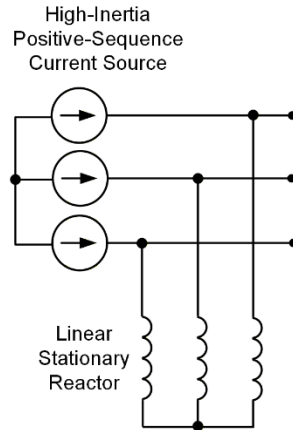


Figure 2 - IBR fault-response model: high-inertia current source behind a shunt reactor.

Our objective is to generate high-fidelity reactor currents based on the IBR terminal voltages, while keeping the source current relatively constant. We can accomplish these design objectives by using the system in **Figure 3**.

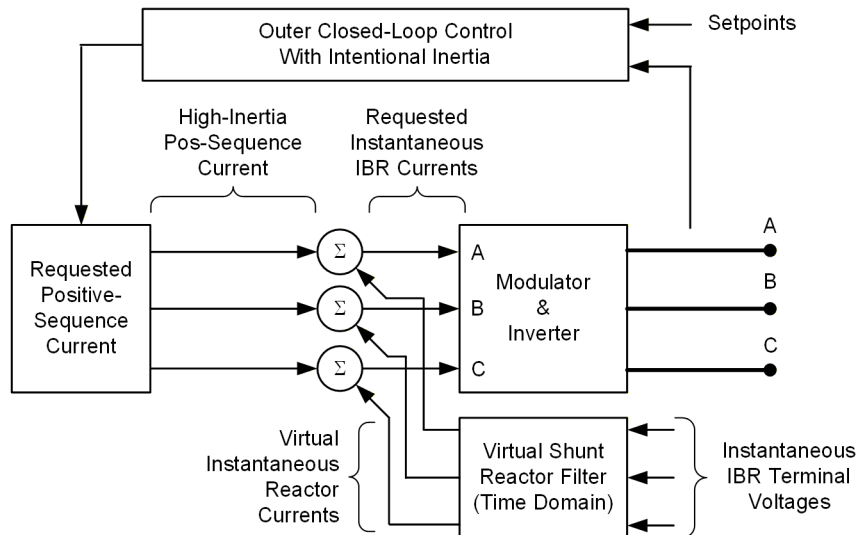


Figure 3 - IBR implementation overview.

The implementation concept in **Figure 3** can be better understood with the following description.

5.1 Control Behavior During Faults

The IBR includes outer control loops to regulate voltage, frequency, power, power factor, droop, and so on. These control loops decide on the current the IBR should provide to the

network, hence the label “requested positive-sequence current” in our description. The outer control loops operate normally during fault conditions. However, these loops are tuned to ride through normally cleared faults (on the order of 4 cycles) or even faults cleared under the breaker failure contingency (on the order of 12 cycles). These loops respond to very slowly cleared faults (on the order of 0.5 s) and during post-fault conditions. Because of the intentional inertia, these control loops do not modulate the current source aggressively and, as a result, the IBR output currents do not change following control algorithms but only by blindly following voltage changes. The source continues to output a positive-sequence current at the pre-fault magnitude, angle, and frequency, with only slow changes resulting from the outer control loops as they follow the system.

Observe that there is no negative-sequence controller in *Figure 3*. The only controlled source is a positive-sequence source, and it is controlled with an intentionally large inertia. Note that the source current is not the IBR output current, and the reactor current makes up the difference.

If fast control action is required, such as to limit the overvoltage across the dc capacitor due to the imbalance between the input (dc) and output (ac) powers, our method requires that these control actions be performed on the input (dc) side, not the output (ac) side. Attempting to control the ac currents during fault conditions is counterproductive for two reasons. First, the fault impacts the effective power out of the IBR, and no control action can override the low-voltage condition, especially because an IBR is a current-limited source. Second, controlling the ac currents for reasons other than voltage-current consistency negatively affects protection.

5.2 Virtual Reactor Implementation

The virtual shunt reactor is implemented as a digital filter in the time domain, and it drives the instantaneous reactor currents based on the instantaneous IBR terminal voltages, according to the R and L parameters of the virtual reactor. The reactor currents are highest under normal voltage conditions (full voltage across the reactor) and reduce when the voltage decreases during fault conditions. The change in the reactor currents follows the change in the IBR terminal voltages, and that change in the reactor currents appears at the IBR terminals because the source current is relatively constant. The net result is that the IBR superimposed currents follow the IBR terminal voltages in a manner consistent with the fixed RL branch.

Reference [2] derives the digital filter required to emulate the virtual shunt reactor. Here, we only reproduce the filter equation and gains, as shown by (1) and (2):

$$i_{A(k)} = G_I \cdot i_{A(k-1)} - G_V \cdot (v_{AB(k)} - v_{CA(k)} + v_{AB(k-1)} - v_{CA(k-1)}) \quad (1)$$

$$G_I = \frac{2 \cdot L \cdot f_s - R}{2 \cdot L \cdot f_s + R} \quad G_V = \frac{1}{3 \cdot (2 \cdot L \cdot f_s + R)} \quad (2)$$

where: A, B, and C are phase designations, f_s is the sampling frequency, and R and L are the virtual reactor parameters.

5.3 Current Synthesis Without Active Control

The reactor currents per (1) have a polarity consistent with the source currents, i.e., the IBR output currents are the sum of the source current and the virtual reactor current. The per-phase sums of the source current and the reactor current are passed to the pulse-width modulator and

inverter. The inverter effectively acts as a current synthesizer, allowing us to produce the required current at the output terminals of the IBR.

Note that there are no controllers in front of the modulator and inverter, and the synthesized current follows the instantaneous values derived from the high-inertia current source and the virtual shunt reactor. As a result, our method does not use active control loops to modulate the current during fault conditions. Instead, it lets the voltages drive the currents in an instantaneous fashion, for all possible voltage-current pairs, including but not limited to the negative sequence, and including but not limited to faults.

6 Fault Example

We use a PSCAD model shown in *Figure 4* and described in detail in [2] to illustrate the proposed method. Reference [2] provides several examples. Here we consider only an evolving AG to ABG fault at the far end of the connecting line. *Figure 5* shows the key signals, including relay voltages and currents (a and b), IBR voltages and currents (f and j), key internal IBR signals (g, h, and i), and selected relay measurements (c, d, and e). We used relay [3] in our tests.

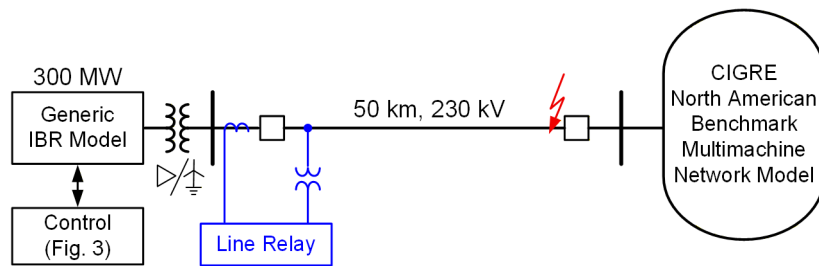


Figure 4 - Simplified system model [2].

The IBR terminal phase-to-phase voltages (f) act as inputs to the virtual shunt reactor filter, see (1), and produce the virtual reactor currents (g). The reactor currents are effectively integrals of the voltages and, therefore, attenuate high-frequency components present in the voltages. These currents follow the laws of physics. Specifically, they contain decaying dc components and do not exhibit step changes. The reactor currents (g) added to the steady-source currents (h) become the input signals to the modulator (i), as per *Figure 3*. The inverter reproduces these currents (i) with high fidelity, resulting in the IBR terminal currents (j). The IBR currents (j) appear at the low-voltage side of the step-up transformer. The high-voltage side currents (b) include the zero-sequence component.

Given the relay voltage (a) and current (b), the relay [3] calculates the negative-sequence (Z_2) and the incremental positive-sequence (ΔZ_1) apparent impedances. The magnitude (c) and angle (d) of these impedances remain steady and as desired. The magnitude and angle values settle immediately after the relay filters settle and are not disturbed by fault evolution. The angle between the negative- and zero-sequence currents (d) is correct and transitions from the ideal 0 degrees for the AG fault to the ideal 120 degrees for the ABG fault, indicating proper current relationships.

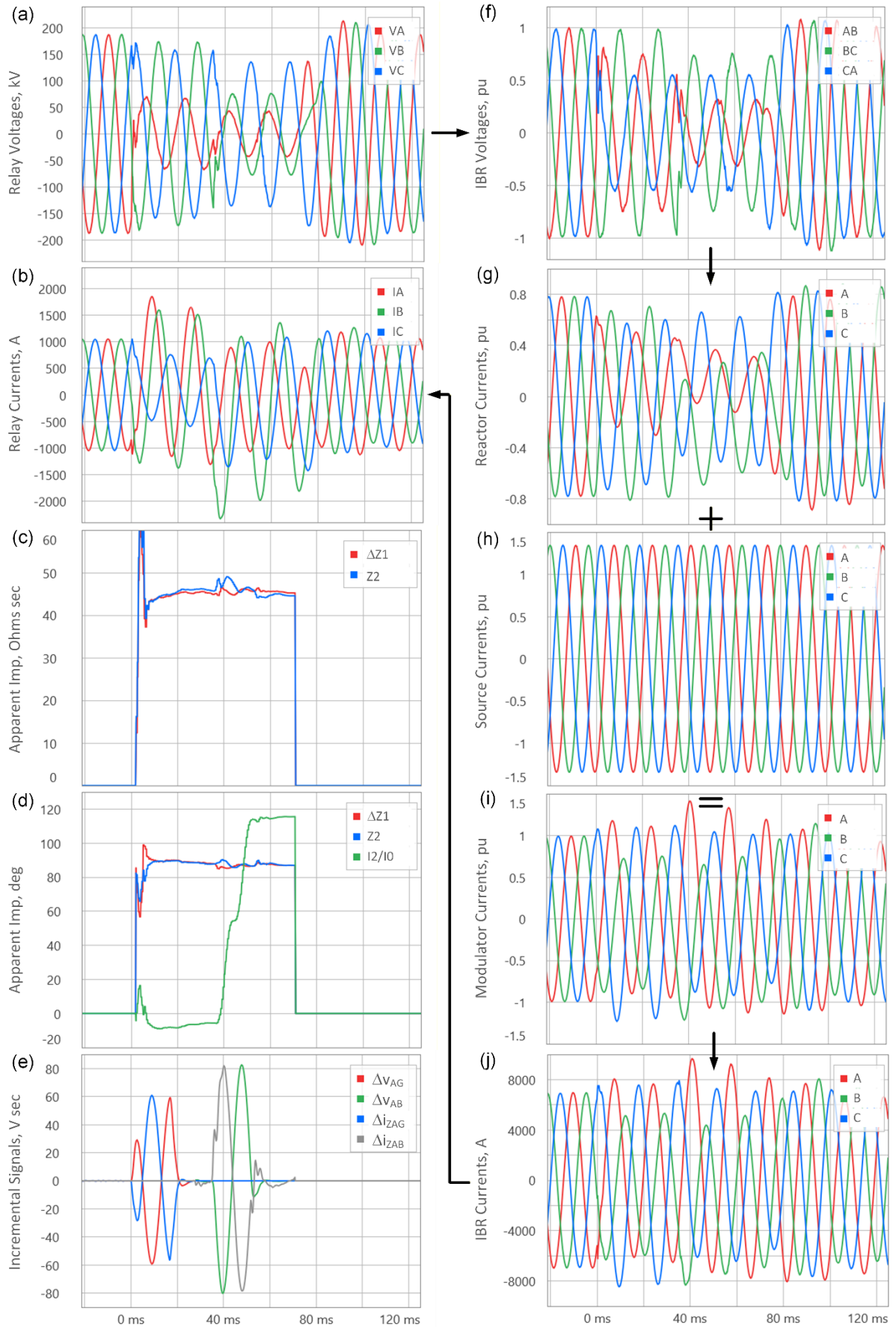


Figure 5 - Key signals during an evolving AG to ABG fault.

The incremental loop voltages and replica currents (e) maintain the correct relationship, acting as mirror images of each other [3] and indicating proper instantaneous signal response for a forward fault.

Figure 5 illustrates signal relationships that are consistent with the model in **Figure 2** and, therefore, support proper operation of directional, distance, and phase selection protection elements.

7 Current Limit Considerations

Figure 6 shows a current phasor diagram during balanced load conditions under nominal voltages. The virtual reactor draws virtual reactive current (I_{REA}) and the current source provides that reactive current component. The closed-loop controllers drive the I_{SRC} current to a point at which the IBR output current I_{IBR} is at the desired magnitude and power factor with respect to the voltage, such as 1 pu magnitude and unity power factor. Effectively, the closed-loop controllers null out the virtual reactor current in the IBR output during steady-state load conditions.

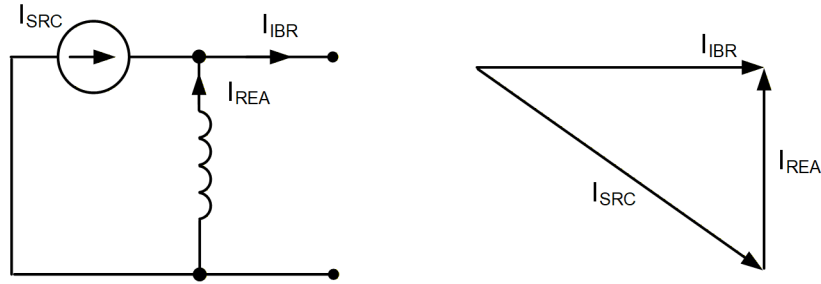


Figure 6 - IBR currents during load conditions and unity power factor.

Figure 7a illustrates the current phasors during a fault. The voltage decreases, resulting in a decrease of the reactor current. With the source current I_{SRC} unchanged, the I_{IBR} output current shifts from the pre-fault value (I_{PRE}). The incremental current ΔI_F is purely reactive. **Figure 7b** shows the case of a bolted fault at the IBR terminals. In this case, the voltage collapses to zero, and the reactor current decreases to zero. As a result, the IBR output current equals the source current, yielding the highest possible fault current.

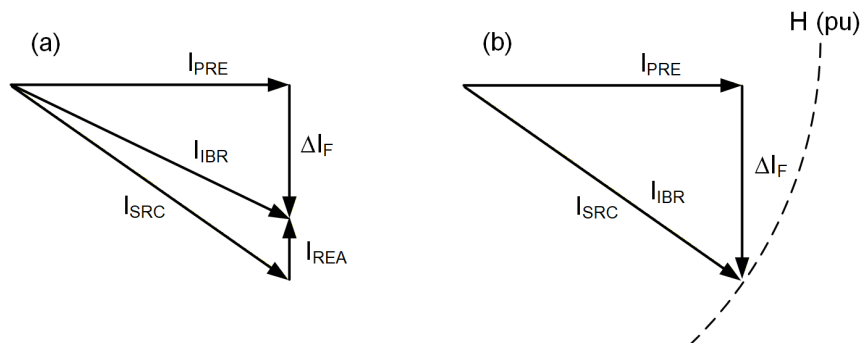


Figure 7 - IBR currents for a general fault (a) and during a bolted close-in fault (b).

Of course, the fault component is purely reactive, and it adds geometrically to the pre-fault current. Assuming full load pre-fault conditions at a unity power factor, and a headroom of H ($H > 1$) as in **Figure 7b**, we calculate the fault component as follows, using (3):

$$\Delta I_F = \sqrt{H^2 - 1} \quad (3)$$

For example, if $H = 1.2$ pu, the fault component is 0.66 pu, and if $H = 1.5$ pu, the fault component is 1.12 pu. At reasonable headroom levels and assuming a significant voltage change, the reactive fault current component in our method is in the same order of magnitude as the active current component.

During remote or high-resistance faults, the voltage changes less than during a close-in bolted fault, and the fault current component is proportionally lower. This is a key difference between the present “negative-sequence injection requirement” and our method. This tradeoff is acceptable, given that the relays of today have good sensitivity and are capable of measuring and acting on relatively small fault current components. Our method uses a fixed RL branch to create a fault current component consistent with voltages and without any time lag, and this advantage outweighs the disadvantage of a lower fault current component.

Figure 7 also serves as another explanation of our method. The method presets the source current to the maximum permissible fault current, assuming the voltage collapses to zero should a fault happen. For any actual voltage collapse, the IBR current is proportional to the voltage change and follows a straight-line trajectory between the pre-fault load current and the source current in **Figure 7b**. Note that **Figure 7** also explains the fault response of a SG, as per **Figure 1b**.

8 Summary and Conclusions

In this paper we presented a simple solution to the IBR fault response challenge that benefits protection systems. Our solution uses the concept of a virtual shunt reactor to make IBR currents follow IBR voltages. The resulting voltage-current relationship is instantaneous and applies in the time domain. By removing the need to use control loops to shape the fault current, our method allows control loops to respond with intentional inertia and separates the fault response from control actions.

By effectively removing control actions during faults, our method allows modeling IBRs for short-circuit studies as a current source behind a fixed impedance and significantly simplifies protection engineering.

The proposed method avoids prioritizing active or reactive power response and instead maintains the pre-fault active current while superimposing reactive current in proportion to the voltage dip and within inverter limits.

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