Behavior of Single-Line-Ground Faults in Inverter-Based Resource Dominated Grids Explained

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***Abstract*—It has been observed by protection engineers that it is difficult for a protective relay to identify the faulted phase during a single-line-ground (SLG) fault in a power system with a high ingression of inverter-based resources (IBR) using currents (phase or sequence). Further studies using electromagnetic transient (EMT) simulation show that the initial operating conditions of the IBRs influence the response of phase currents during an SLG fault. In this letter, we conduct a quantitative analysis using sequence components. We find that the pre-fault condition determines the relative position of the current contributed by the grid vs. that by the IBR and further determines which phase has the largest magnitude during an SLG condition. This finding is further verified by the EMT simulation results.**

***Index Terms*—Inverter-based resource, single-line-ground faults, fault analysis, electromagnetic transient simulation.**

I. INTRODUCTION

IT has been observed by protection engineers that it is difficult for a protective relay to identify the faulted phase during a single-line-to-ground (SLG) fault using current (phase or sequence) in a power system with a high ingress of inverter-based resources (IBR). In 2020, Normann Fischer published a blog in the Energy Systems Integration Group (ESIG) website titled "Protection of Inverter-Based Resources" [1] and compared the dynamic behavior of a conventional generator and an IBR for a SLG fault. Fig. 1 shows the circuit diagram of the system topology, fault location, and the relay's location, while Fig. 2 shows the oscillography for a metallic AG fault on the line at the Terminal S with either a synchronous generator behind Bus S or an IBR behind Bus S.

It can be seen from Fig. 2 that the voltage responses are similar in the two cases with the phase A voltage dropping to zero, while the voltages of the other two phases remain close to the nominal level. The current responses are significantly different. In a conventional grid, phase A current has the highest magnitude if the SLG fault is an AG fault, as shown in Fig. 2(a). On the other hand, the B-phase current has the highest magnitude in the IBR case, as shown in Fig. 2(b). This observation may imply that this is a BG fault, while this is in fact an AG fault. Fischer made the following comments regarding Fig. 2(b) the IBR case: (i) "the phase currents are almost in phase with one another (this is due to the high zero-sequence current)"; (ii) " ... the phase currents are a composite of the inverter current (positive- and negative-sequence current) and the system current (zero-sequence current). This composition

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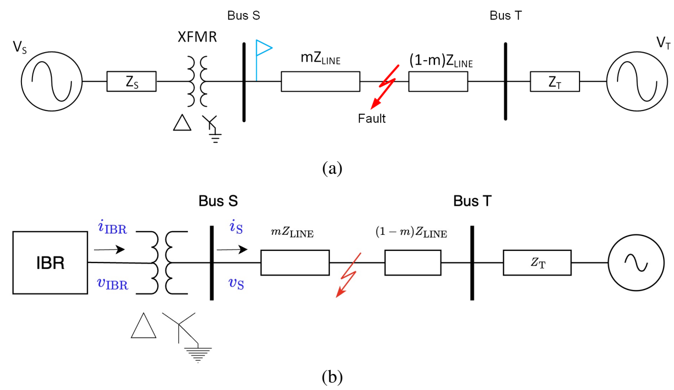


Fig. 1: (a) A simple power system with conventional synchronous generator power sources. The relay is located at Bus S [1]. (b) A simple power system with an IBR.

of the phase current results in some very interesting currents during fault conditions."

In this research, we present a quantitative analysis and examine Fischer's remarks to find out why an AG fault does not appear like an AG fault. In addition, we set up a power system testbed with a high IBR's penetration in an EMT simulation environment to conduct further investigation. The IBR controls (inner current control, phase-locked loop, and outer control in the PQ regulation mode) are included in the model. Details of the IBR controls can be found in [2]. The EMT simulation results show that the initial operating conditions of the IBRs during fault conditions.

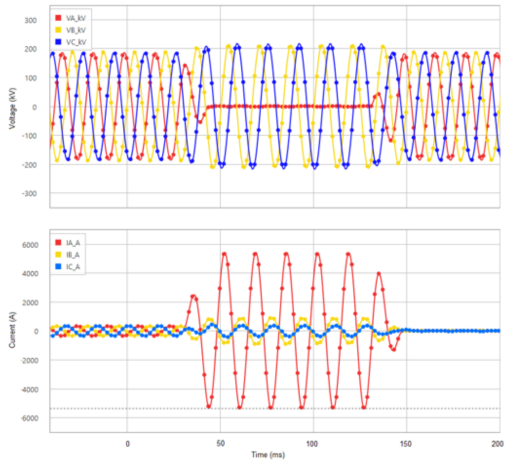
It is worth mentioning that the IBRs considered in this paper may not meet the IEEE standard 2800-2022's requirement for providing negative sequence currents. On the other hand, since many conventional IBRs have been deployed in the field and are currently operational, this research is relevant to the industry by providing a better understanding.

In Section II of this letter, we first examine the waveform presented in [1]. Then we derive an interconnected sequence network, and carry out fault analysis. EMT simulation results are also presented. In Section III, we conclude the paper.

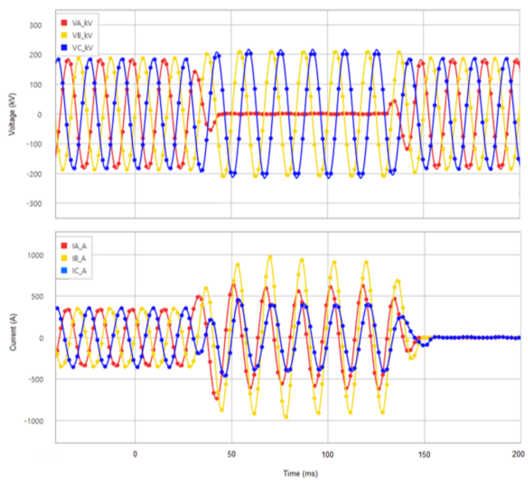
II. INTERCONNECTED SEQUENCE NETWORK DERIVATION

A. PNZ components of the measured current

Based on Fig. 2(b), we first conduct numerical analysis to compute the positive-, negative-, and zero-sequence (PNZ) current components from the phase currents measured by the relay. The values are listed in Table I, while the waveforms of the phase current and its PNZ components are shown in Fig. 3. The phase current phasors are obtained by visually examining the waveforms in Fig. 2(b). Therefore, those are estimated



(a)



(b)

Fig. 2: The oscillography for a metallic AG fault on the line at Terminal S, (a) with a synchronous generator as a source behind Bus S; (b) with a full inverter IBR as a source behind Bus S [1].

phasors. The corresponding instantaneous waveforms are further plotted in Fig. 3 to again visually benchmark with those waveforms shown in Fig. 2(b).

TABLE I: The abc and PNZ of the measured currents (unit: kA)

abc	$0.6\angle 0°$	$1\angle -30°$	$0.4\angle -45°$
PNZ	$0.31\angle 76°$	$0.06\angle -145°$	$0.64\angle -24°$

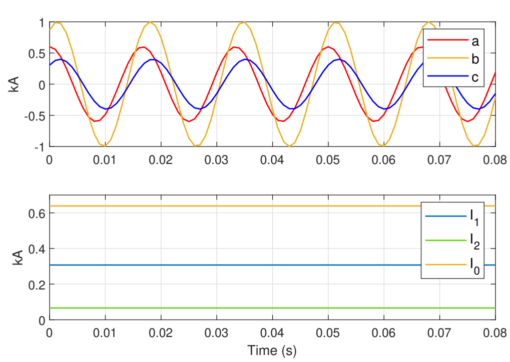


Fig. 3: The symmetrical components of the measured currents.

Numerical analysis shows that the positive-sequence current magnitude is approximately 310 A. This magnitude aligns with the prefault current magnitude. Additionally, analysis shows that the negative-sequence current is very small (approximately 60 A), and the zero-sequence component dominates the PNZ components (approximately 640 A). The analysis proves that the IBR is a constant current source. It maintains the positive-sequence current magnitude while injecting insignificant negative-sequence current during fault, which further implies that an IBR can be treated as a positive-sequence current source with a large negative-sequence impedance. These observations will be used to construct the sequence circuits.

B. Interconnected sequence network

The source connected to Bus S is an IBR and the interconnected sequence network for the SLG fault is derived and presented in Fig. 4. It is to be noted that in the positive-sequence network, the IBR is represented by a current source $\overline{I}_S$, while in the negative-sequence network, the IBR is represented by a very large impedance or simply an open circuit. In the zero-sequence network, the Δ/Y_g transformer at the point of interconnection (POI) provides a zero sequence sink. Another fact to be noted is that the contribution of fault current from the grid voltage source $\overline{V}_T$ is also included.

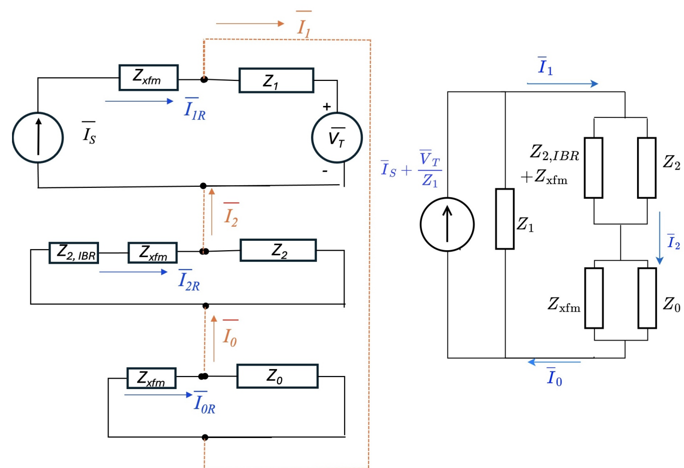


Fig. 4: The interconnected sequence network. The subscript "R" notates the measurements sensed by the relay. Z_1, Z_2 and Z_0 are the PNZ impedances of the transmission line. Z_{xfm} is the impedance of the transformer.

The following assumptions are made for numerical analysis. First, the negative-sequence impedance of the IBR $Z_{2,\text{IBR}}$ is very large. Therefore, the negative-sequence current component $\overline{I}_{2R}$ calculated by the relay is very small. This branch can be viewed as an open circuit. Therefore the two parallel branches Z_2 and $Z_{2,\text{IBR}} + Z_{\text{xfm}}$ are equivalent to the Z_2 branch only. Second, the line's zero-sequence impedance is much larger than the transformer's impedance. Therefore, the resulting impedance of the two parallel branches Z_0 and Z_{xfm} can be viewed as Z_{xfm} only. Additionally, Z_{xfm} is small compared to Z_2 while Z_1 and Z_2 have comparable values. Therefore, the PNZ-components of the fault current are about

TABLE II: Three cases of different initial operating condition

case	P (MW)	Q (MVAr)	$\overline{I}_S$ (kA)	$\overline{V}_{\mathrm{POI}}$	$\overline{I}_{aR}$ (kA)	$\overline{I}_{bR}$ (kA)	$\overline{I}_{cR}$ (kA)
1	46	54	$0.31\angle 0^\circ$	$1.18\angle 57^\circ$	$\mathbf{0.96}\angle -25^\circ$	$0.80\angle -47^\circ$	$0.59\angle -23^\circ$
2	82	-27	$0.31\angle 77^\circ$	$0.93\angle 51^\circ$	$0.66\angle 3^\circ$	$\mathbf{0.94}\angle -30^\circ$	$0.45\angle -50^\circ$
3	-28	12	$0.1\angle -115^\circ$	$1.02\angle 41^\circ$	$0.73\angle -48^\circ$	$0.60\angle -39^\circ$	$\mathbf{0.77}\angle -35^\circ$

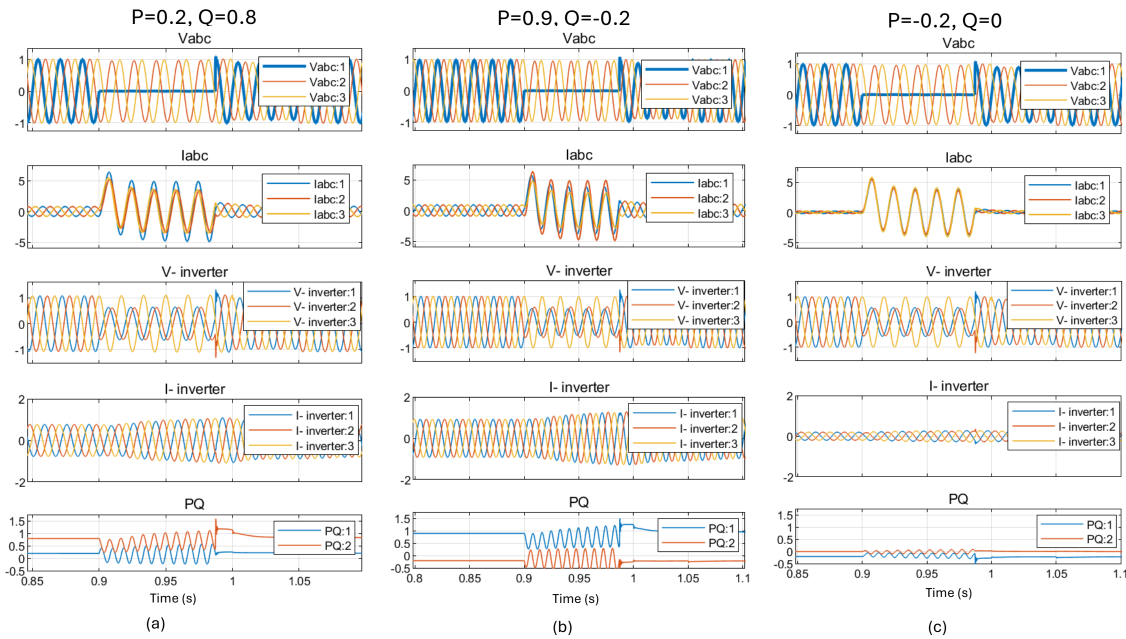


Fig. 5: EMT simulation results for a metallic AG fault on the line at Terminal S when the IBR's PQ exporting levels are different. (a) $P = 0.2, Q = 0.8$, Phase-A current is dominant. (b) $P = 0.9, Q = -0.2$, Phase-B current is dominant. (c) $P = -0.2, Q = 0$, Phase-C current is dominant.

0.5 times of the total current injection $\overline{I}_S + \frac{\overline{V}_T}{Z_1}$.

$$\overline{I}_1 = \overline{I}_2 = \overline{I}_0 = \frac{1}{2}\left(\overline{I}_S + \frac{\overline{V}_T}{Z_1}\right) \tag{1}$$

Apparently, a fault impedance (usually resistive) leads to reduced sequence currents. The bolted fault scenario is the worst-case scenario; hence, this paper focuses on bolted faults. We now evaluate the sequence components and the phase currents measured by the relay. The positive-sequence current $\overline{I}_{1R}$ is the same as $\overline{I}_S$. The negative-sequence current $\overline{I}_{2R}$ is 0. And the zero-sequence current $\overline{I}_{0R}$ is the same as $\overline{I}_0$ since Z_0 is much greater than Z_{xfm} and the majority if not all of the zero-sequence fault current takes the path of the transformer.

$$\overline{I}_{1R} = \overline{I}_S,\ \overline{I}_{2R} = 0,\ \overline{I}_{0R} = \frac{1}{2}\left(\overline{I}_S + \frac{\overline{V}_T}{Z_1}\right) \tag{2}$$

Therefore, the phase currents measured by the relay can be computed as (3). If the IBR is not connected to the system during an SLG fault at Bus S, the currents seen by the relay are zero-sequence currents contributed by the grid source. On the other hand, if the IBR is connected and exporting power (real and apparent), the PZ-components of the current will be different depending on the load. In turn, which phase has dominant current varies. In the following examples, we demonstrate three cases, each with either Phase-A, Phase-B, or Phase-C as the dominant current.

$$\begin{aligned}
\overline{I}_{aR} &= \overline{I}_S + \overline{I}_{0R} = \frac{3}{2}\overline{I}_S + \frac{1}{2}\frac{\overline{V}_T}{Z_1},\\
\overline{I}_{bR} &= \alpha^2\overline{I}_S + \overline{I}_{0R} = -j\frac{\sqrt{3}}{2}\overline{I}_S + \frac{1}{2}\frac{\overline{V}_T}{Z_1},\\
\overline{I}_{cR} &= \alpha\overline{I}_S + \overline{I}_{0R} = j\frac{\sqrt{3}}{2}\overline{I}_S + \frac{1}{2}\frac{\overline{V}_T}{Z_1}
\end{aligned} \tag{3}$$

In all three cases, the contributing current source from the grid is the same: $\frac{\overline{V}_T}{Z_1} = 1.37\angle -36.86^\circ$ kA (assuming $\overline{V}_T = 1\angle 45^\circ$ pu and $Z_1 = 0.03 + j0.217$ pu based on the power base of 90 MW and voltage amplitude base of 200 kV). The three cases differ at the initial condition or the IBR's current source $\overline{I}_S$. Table II lists the IBR's exporting powers (P and Q), the POI bus voltage phasor $\overline{V}_{\mathrm{POI}}$, the injected current phasor $\overline{I}_S$, and the computing results of the phase currents due to the AG fault.

Remarks: It can be seen that the relative positions of the IBR's current phasor and the grid's contribution to fault current determine which phase has a dominant current for the AG fault. If the IBR's current source and the grid's fault current contribution are aligned with each other (case 1), Phase A current is dominant. If the grid's fault current contribution is more aligned to the IBR current phasor rotating backward (forward) by 90 degrees, Phase-B (C) current is dominant.

For an inductive transmission network, the grid's fault current contribution lags the grid voltage by approximately 90 degree. Therefore, for case 1, the IBR current phasor lags the grid voltage. This means the IBR is exporting real and reactive power. For Phase-B current to be dominant, the IBR's current phasor approximately aligns with the grid voltage phasor. For Phase-C current to be dominant, the IBR's current phasor is approximately out-of-phase with the voltage phasor. In this case, the IBR absorbs real power (a battery is getting charged).

C. EMT simulation results

An EMT testbed is built to represent the simple power system in Fig. 1 where an IBR is connected to Bus S through a Δ/Y_g transformer. The IBR is represented by a constant DC voltage interfaced to the AC grid through a grid-following voltage-sourced converter (VSC). The IBR model built in MATLAB/Simscape can be found in the Github repository [3]. The grid-following control has inner current control implemented in the dq-frame, or the phase-locked loop (PLL) frame, outer control in P and Q regulation mode, and a synchronizing unit (PLL). The transmission line has an impedance of $0.02 + j0.2$ pu. The AG fault is applied at Bus S. The current responses for three operating conditions are presented: (a) $P = 0.2, Q = 0.8$, (b) $P = 0.9, Q = -0.2$, (c) $P = -0.2, Q = 0$. Fig. 5 shows the voltage and current measurements at the relay and the inverter terminals for three operating conditions. It can be seen that for each case, a different phase has a dominant current observed by the relay.

In all cases, there is a high zero-sequence component in the phase currents, causing the three-phase currents to be almost in phase with each other. Additionally, the IBR's current remains within the current limit of 2 p.u. before and after the fault.

III. Conclusion

We find that for unbalanced faults in an area with high IBR penetration, fault currents exhibit high zero-sequence components, leading to comparable magnitudes across the three phases and making it difficult to detect the faulted phase. Additionally, the relative position of the positive-sequence current contribution from the IBR versus that from the grid source determines which phase has a dominant current in an SLG fault. In other words, initial operating condition of the IBRs influences the current responses for SLG faults.

References

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