PERFORMANCE OF DISTANCE PROTECTION UNDER INVERTER-BASED RESOURCES WITH IEEE 2800 CURRENT INJECTION REQUIREMENTS

Xinquan Chen[1], Siqi Bu[1], Aboutaleb Haddadi[3], and Ilhan Kocar[1,2*]
[1]Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China.
[2]Polytechnique Montréal, Montreal, QC H3T 1J4, Canada.
*ilhan.kocar@polymtl.ca
[3]Electric Power Research Institute (EPRI)

0. Abstract

Fault ride-through (**FRT**) mode: current injection requirements for inverter-based resources (**IBRs**)

The impact of IBRs on system protection may vary depending on the requirements in codes

This may challenge protective relaying

The impacts of IEEE 2800 current injection requirements on distance protection.

- We develop a specified current-limiting scheme to comply with the IEEE 2800 standard.
- During unbalanced faults, the impacts of the current injection on apparent impedance are elaborated analytically.
- In a modified IEEE PSRC D29 system with IBRs, the performance of distance protection is investigated under varying impact factors, including K factors, fault proximity, and fault resistance.

1.1 Background

- Inverter-based resources (IBRs) play a vital role in future power systems with high penetration of renewable energy sources (RESs) [1].
- The IEEE 2800 standard provides minimum technical interconnection requirements for IBRs, such as wind turbine generators (WTGs) [2].
- Clause 7.2.2 of IEEE 2800 has specified the performance required of an IBR during FRT. The clause requires an IBR to inject positive sequence reactive current (I1R) and negative sequence reactive current (I2R) during unbalanced faults. Moreover, the converter current capacity shall be fully utilized, and the negative-sequence current (I2) shall lead the negative-sequence voltage (V2) at the point of connection (POC) by 90-100˚ for full converter-based IBRs and 90-150˚ for Type-III WTGs.

- As transmission system operators and owners develop their IBR interconnection requirements and consider the adoption of IEEE 2800, it is essential to understand the implications of those requirements on the bulk power system to ensure reliable integration of IBRs.
- This paper studies the impact of IBR fault ride-through (FRT) performance requirements of IEEE 2800 on distance protection.

[1] B. Kroposki et al.: 'Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy', IEEE Power and Energy Magazine, 2017, 15, (2), pp. 61-73
[2] 'IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems,' IEEE Std 2800-2022, 2022, pp. 1-180

1.2 Literature review

- Distance protection typically utilizes the calculated apparent impedance of the fault loop to identify the faulted zone.
- In an IBR-rich system, the apparent impedance may be affected by the FRT behavior of IBRs [3], [4].
- The absence of properly defined IBR FRT requirements may potentially lead to incorrect operation of a distance relay.
- To avoid protection misoperation, researchers have proposed enhanced fault coordination control schemes for IBRs in various fault scenarios [5], [6].
- References [7]−[9] study the impacts of IBRs on different types of distance relays.

However, existing studies on distance protection in IBR-integrated systems do not consider the current injection requirements of the IEEE 2800 standard, which is addressed in this paper.

[3] A. Haddadi, E. Farantatos, I. Kocar, and U. Karaagac, 'Impact of Inverter Based Resources on System Protection,' Energies, 2021, 14, (4)
[4] A. Hooshyar, M. A. Azzouz, and E. F. El-Saadany, 'Distance Protection of Lines Emanating From Full-Scale Converter-Interfaced Renewable Energy Power Plants—Part I: Problem Statement,' IEEE Trans. Power Del., 2015, 30, (4), pp. 1770-1780
[5] A. Banaiemoqadam, A. Hooshyar, and M. A. Azzouz, 'A Control-Based Solution for Distance Protection of Lines Connected to Converter-Interfaced Sources During Asymmetrical Faults,' IEEE Trans. Power Del., 2020, 35, (3), pp. 1455-1466
[6] A. Banaiemoqadam, A. Hooshyar, and M. A. Azzouz, 'A Comprehensive Dual Current Control Scheme for Inverter-Based Resources to Enable Correct Operation of Protective Relays,' IEEE Trans. Power Del., 2021, 36, (5), pp. 2715-2729
[7] A. Banaiemoqadam, A. Azizi, A. Hooshyar, M. Kanabar, and E. F. El-Saadany, 'Impact of Inverter-Based Resources on Different Implementation Methods for Distance Relays—Part I: Phase Comparators,' IEEE Trans. Power Del., 2023, 38, (6), pp. 4090-4102
[8] A. Banaiemoqadam, A. Azizi, A. Hooshyar, and E. F. El-Saadany, 'Impact of Inverter-Based Resources on Different Implementation Methods for Distance Relays—Part II: Reactance Method,' IEEE Trans. Power Del., 2023, 38, (6), pp. 4049-4060
[9] A. Haddadi, M. Zhao, I. Kocar, E. Farantatos, and F. Martinez, 'Impact of Inverter-Based Resources on Memory-Polarized Distance and Directional Protective Relay Elements,' in 2020 52nd North American Power Symposium (NAPS), 2021, pp. 1-6

1.3 Contribution

This paper implements a FRT control and current limiter scheme for a Type-IV WTG conforming with IEEE 2800 requirements.

- Under FRT mode, the interaction between current injection and apparent impedance is elaborated analytically.
- During unbalanced faults, the performance of distance protection is examined using a modified IEEE PSRC D29 system integrated with Type-IV WTGs.
- The protection performance under the specified scheme and conventional FRT scheme are compared under varying impact factors, including K factors, fault proximity, and fault resistance.

2. Implementation of IEEE 2800 current injection requirements on IBRs

Fig. 1 shows the typical decoupled-sequence control in the grid-side converter (GSC) of Type-IV WTGs. To comply with the IEEE 2800 standard, the specified current limiting scheme is implemented prior to the inner control. Superscripts + and − denote positive and negative sequence components, respectively.

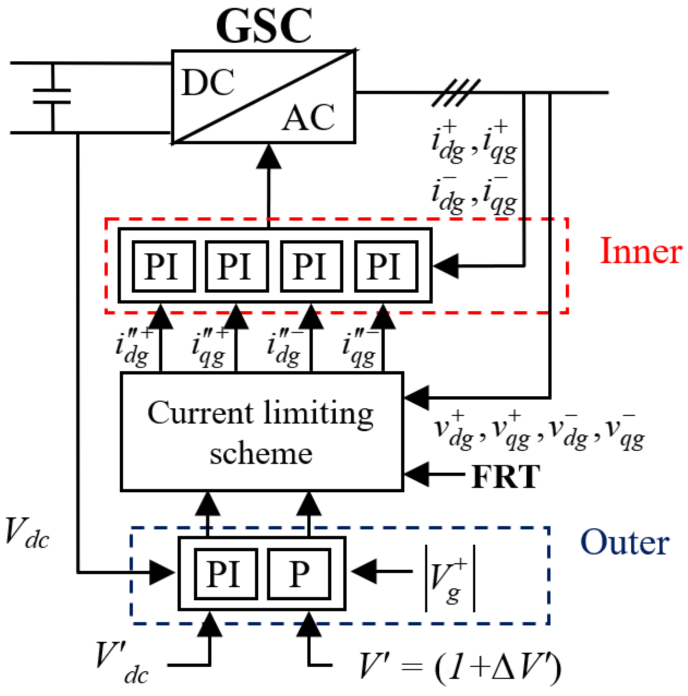

Fig. 1 Decoupled-sequence GSC control of Type-IV WTGs

In normal operation, the current priority is given to the *d*-axis current, as given by

$$\begin{cases} \left| i'^{+}_{dg} \right| \le i_{\max} \\ \left| i'^{+}_{qg} \right| \le \sqrt{i_{\max}^{2} - (i'^{+}_{dg})^{2}} \end{cases}$$

where i_{max} denotes the maximum current limit. Under FRT mode, the provisions in Clause 7.2.2.3.4 of the IEEE 2800 standard should be considered. The details of the proposed current-limiting scheme under FRT mode are illustrated as follows:

Provision 1: The incremental I1R (i_Q^{+inc}) shall not be reduced below incremental I2R (i_Q^{-inc}). By using the *K*-factor-based method, I1R and I2R are determined as

$$\begin{cases} i_Q^{+inc} = K^{+}\left(1 - V_g^{+}\right) \\ 0 \le i_Q^{-inc} = K^{-}V_g^{-} \le i_Q^{+inc} \end{cases}$$

2. Implementation of IEEE 2800 current injection requirements on IBRs

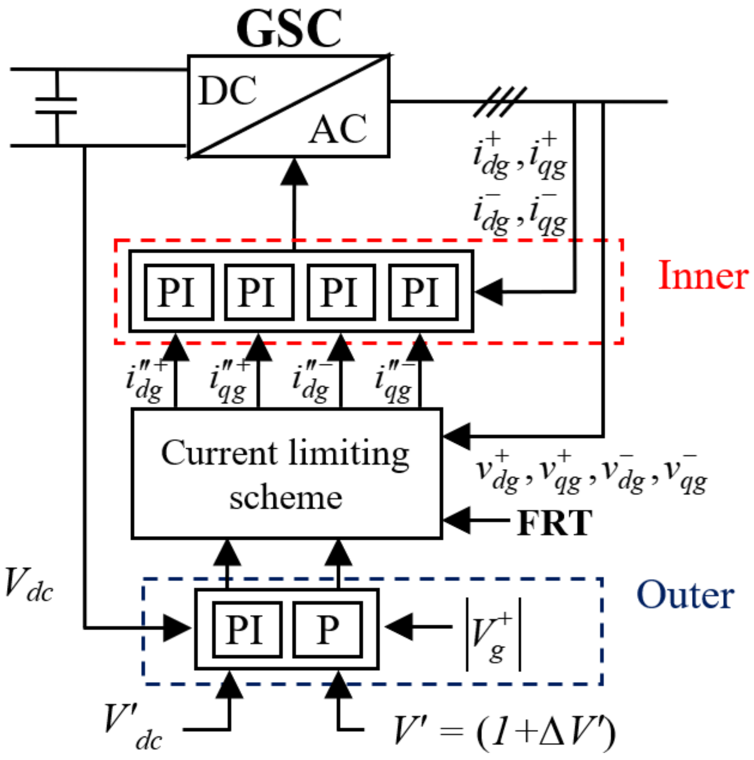

Fig. 1 Decoupled-sequence GSC control of Type-IV WTGs

Provision 2: If the maximum current limit is reached, either I1R, or I2R, or both may be reduced with a preference of equal reduction in both currents. To comply with this, a reactive current scaling method is used to reduce the incremental reactive current, as follows:

$$\begin{cases} K_{scaleQ} = \left(i_{\max} - i_Q^{+pre} \right) \Big/ \left(i_Q^{+inc} + i_Q^{-inc} \right) \\ i_Q = K_{scaleQ} i_Q^{+inc} + i_Q^{+pre} + K_{scaleQ} i_Q^{-inc} \end{cases}$$

where K_{scaleQ} denotes the scaling factor for reactive current. i_Q^{+pre} denotes the pre-fault I1R. For the positive sequence current limiter, the priority is given to the I1R under FRT mode, as given by

$$\begin{cases} \left| i_{dg}'^{+} \right| \le \sqrt{\left(i_{\max} - K_{scaleQ} i_{Q-}^{inc} \right)^2 - \left(i_{qg}'^{+} \right)^2} \\ i_{qg}'^{+} = K_{scaleQ} i_{Q+}^{inc} + i_Q^{+pre} \le i_{\max} - K_{scaleQ} i_{Q-}^{inc} \end{cases}$$

2. Implementation of IEEE 2800 current injection requirements on IBRs

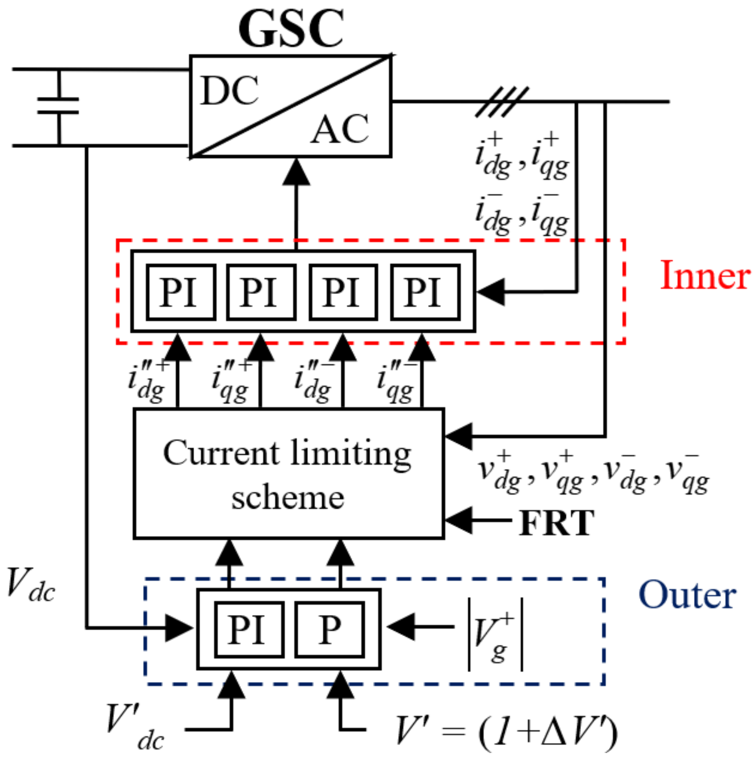

Fig. 1 Decoupled-sequence GSC control of Type-IV WTGs

Provision 3: I2 leads the IBR unit terminal V2 by 90° to 100° for full converter-based IBRs. To ensure that I2 should lead V2 by 90°, the dq references of I2 are determined as

$$\begin{cases} i'^{-}_{dg} = v^{-}_{qg} K_{scaleQ} i^{inc}_{Q-} \big/ V^{-}_{g} \\ i'^{-}_{qg} = -v^{-}_{dg} K_{scaleQ} i^{inc}_{Q-} \big/ V^{-}_{g} \end{cases}$$

Provision 4: IBRs shall be capable of injecting current to the maximum current limit. To fully utilize the current capacity, the positive and negative sequence current references can be converted to phase current references. Then a phase current scaling method can be used to ensure maximum phase current to reach the current limit, as given by

$$\begin{cases} i'_{a} = i'^{+}_{g} + i'^{-}_{g} \\ i'_{b} = i'^{+}_{g} e^{j240°} + i'^{-}_{g} e^{j120°} \\ i'_{c} = i'^{+}_{g} e^{j120°} + i'^{-}_{g} e^{j240°} \end{cases} \qquad K_{scale-ph} = \frac{i_{\max}}{\max(i'_{a}, i'_{b}, i'_{c})}$$

$$\left\{ i''^{+}_{dg} \;\; i''^{+}_{qg} \;\; i''^{-}_{dg} \;\; i''^{-}_{qg} \right\} = K_{scale-ph} \left\{ i'^{+}_{dg} \;\; i'^{+}_{qg} \;\; i'^{-}_{dg} \;\; i'^{-}_{qg} \right\}$$

3. Interaction between current injection and apparent impedance under FRT mode

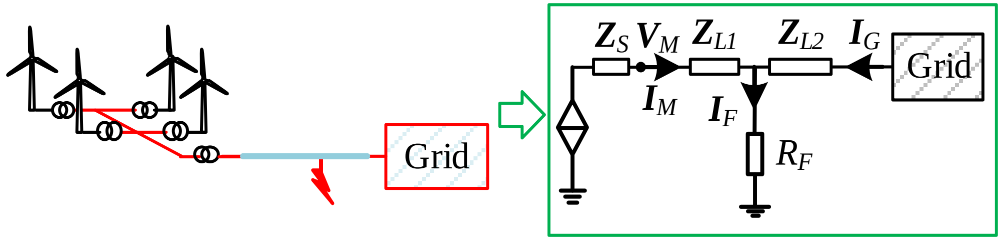

Fig. 2 Transmission system with IBR and the equivalent circuit

IBRs can be equivalent to controlled current sources under FRT mode since they are required to inject specified current per grid codes. Fig. 2 shows a simple transmission system with an IBR and its equivalent circuit for the purpose of illustration.

$\{\boldsymbol{V}_M, \boldsymbol{I}_M\}$: voltage and current vectors measured by the distance relay at the IBR terminal.

$\boldsymbol{Z}_s$: the equivalent impedance of IBR.

$\boldsymbol{I}_G$: the current contribution from the external grid.

R_F : the fault resistance.

$\{\boldsymbol{Z}_{L1}, \boldsymbol{Z}_{L2}\}$: the equivalent impedance from fault points to each terminal.

The apparent impedance:

$$\boldsymbol{Z}_M = \frac{\boldsymbol{V}_M}{\boldsymbol{I}_M} = \frac{\boldsymbol{I}_M \boldsymbol{Z}_{L1} + \boldsymbol{I}_F R_F}{\boldsymbol{I}_M} = \boldsymbol{Z}_{L1} + \frac{(\boldsymbol{I}_M + \boldsymbol{I}_G) R_F}{\boldsymbol{I}_M} = \boldsymbol{Z}_{L1} + \left(1 + \frac{\boldsymbol{I}_G}{\boldsymbol{I}_M}\right) R_F$$

$\boldsymbol{I}_M$ is determined by the current limiting scheme

$$\begin{cases} |\boldsymbol{I}_M| = |i_g^+ + i_g^-| \\ \measuredangle \boldsymbol{I}_M = \measuredangle (i_g^+ + i_g^-) \end{cases}$$

With the specified scheme

$$\begin{cases} |\boldsymbol{I}_M| = i_{\max} \\ \measuredangle \boldsymbol{I}_M = \measuredangle (\boldsymbol{I}_P^+ + \boldsymbol{I}_Q^+ + \boldsymbol{I}_Q^-) \\ |\boldsymbol{I}_Q^+| = K_{scale-ph} \left(K_{scaleQ} K^+ (1 - V_g^+) + i_Q^{+pre}\right) \\ |\boldsymbol{I}_Q^-| = K_{scale-ph} K_{scaleQ} K^- V_g^- \end{cases}$$

$\boldsymbol{I}_P$ and $\boldsymbol{I}_Q$ denote active and reactive currents.

The apparent impedance $\boldsymbol{Z}_M$ can be altered by the $\boldsymbol{Z}_{L1}$, R_F, and $\{K^+, K^-\}$. These impact factors represent the fault proximity, fault resistance, and K factors for reactive current injection, respectively.

4. Performance of distance protection in the system with IBRs considering IEEE 2800 current injection requirements

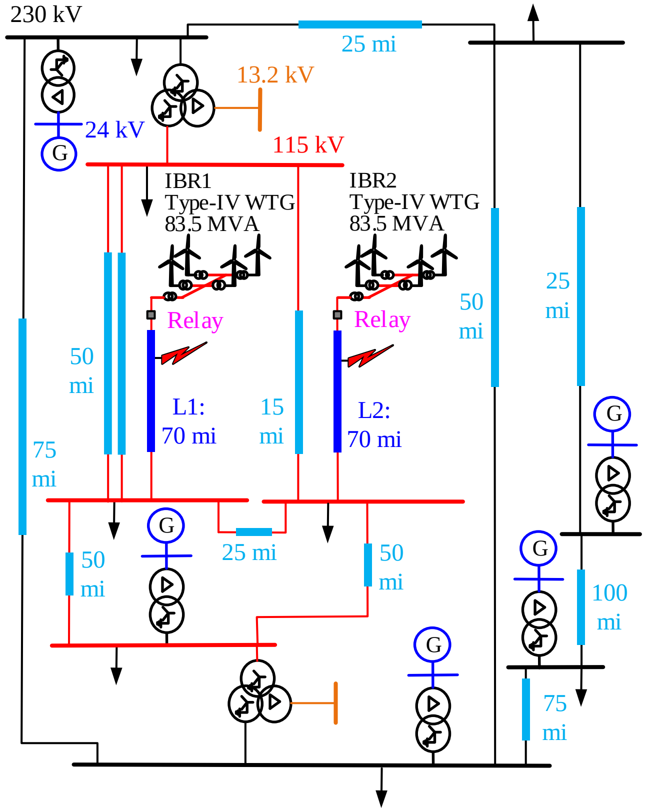

Fig. 3 Modified IEEE PSRC D29 system integrated with Type-IV WTGs

A modified IEEE PSRC D29 system integrated with Type-IV WTGs is used for validation.

- Distance relays are located at the point of interconnection (POI) of IBR1 and IBR2.
- IBR1 employs the specified current-limiting scheme that meets the IEEE 2800 standard, while IBR2 employs the conventional FRT scheme that meets German grid codes [10].
- The manufacturer of distance relays is Generic Electric. The model is GE 60.

Table A1 Protection configuration and line parameters

Protection Functions and Settings		Value
Distance protection	direction	Forward
	shape	Quad
	RCA	85°
	range (zone 1/2/3)	80% / 135% / 200%
	delay (zone 1/2/3)	0 / 20 / 40 cycles
	VT ratio	115000:115
	CT ratio	500:5
Transmission line	R1/X1/B1	5.87/ 38.29/ 2.79e-4 Ω
	R0/X0/B0	33.3/ 115.9/ 1.79e-4 Ω

[10] U. Karaagac et al., 'A Generic EMT-Type Model for Wind Parks With Permanent Magnet Synchronous Generator Full Size Converter Wind Turbines,' IEEE Power and Energy Technology Systems Journal, 2019, 6, (3), pp. 131-141

4.1 Performance under Varying Fault Proximity

10 Ω line-A-to-ground (AG) faults are applied at transmission lines L1 and L2 when t=2 s.

The fault distance is set to 30 miles, 45 miles, and 55 miles, respectively. The fault duration is set to 1 s.

Figs. 4–6 show the phase A current angle and reactive current injection under the specified scheme (IBR1) and the conventional FRT scheme (IBR2). Longer fault distance causes a larger current angle and a smaller reactive current injection.

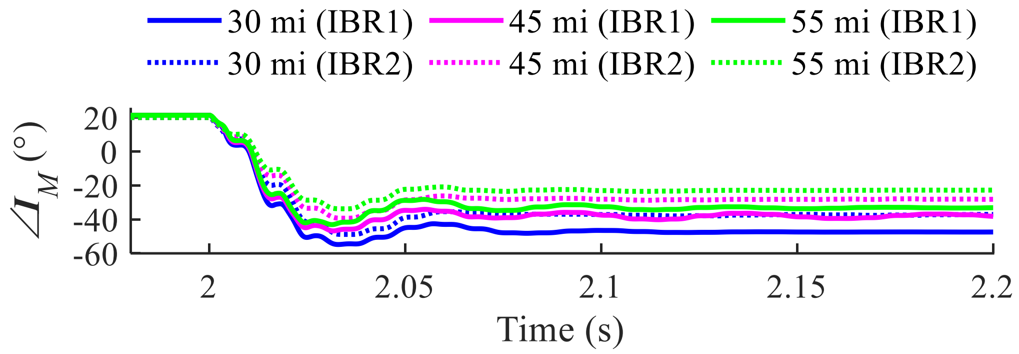

Fig. 4. Current angle $\measuredangle \boldsymbol{I}_{Ma}$ under varying fault proximity

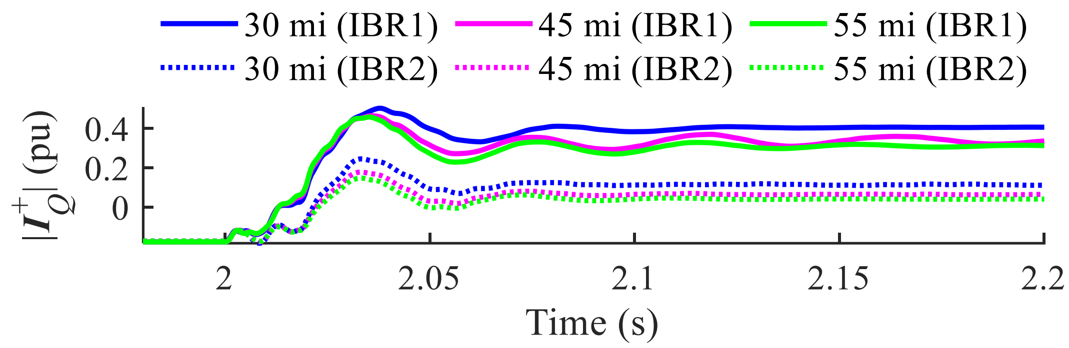

Fig. 5. I1R injection under varying fault proximity

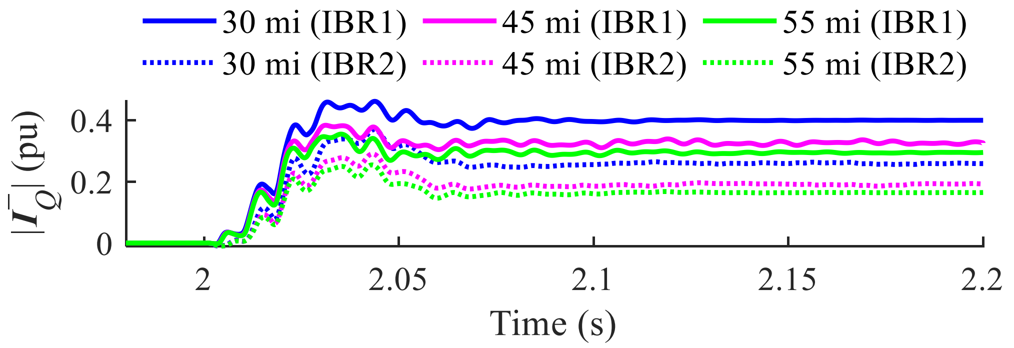

Fig. 6. I2R injection under varying fault proximity

4.2 Performance under Varying Fault Proximity

Fig. 7 shows the apparent impedance locus under the specified scheme (IBR1) and the conventional FRT scheme (IBR2), where red and black lines denote the border of zone 1 and zone 2, respectively.

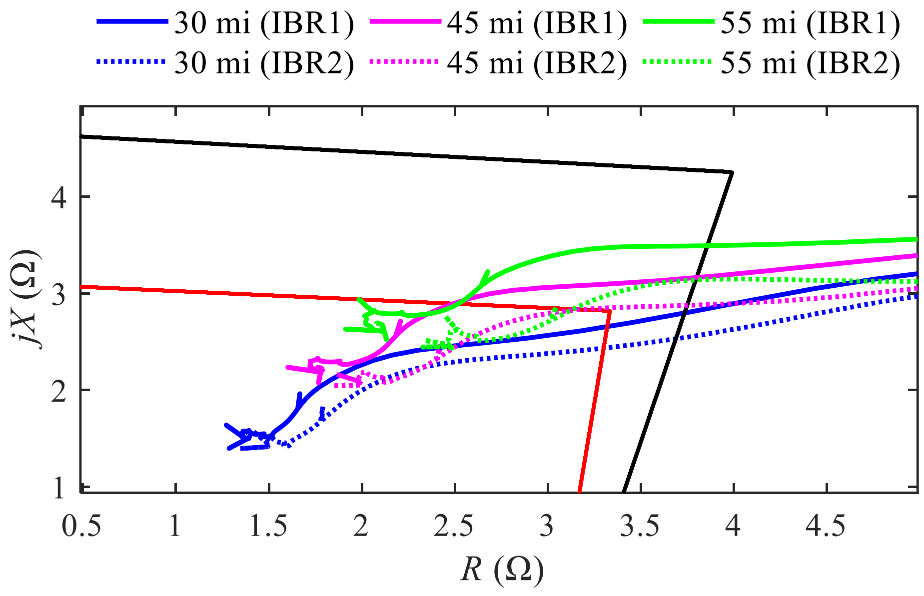

Fig. 7. Apparent impedance $\boldsymbol{Z}_M$ under varying fault proximity

The results show that IBR1 exhibits greater reactive current injection than IBR2 since the current capacity of IBR1 is fully utilized. Under the two FRT schemes, Zone 1 can correctly trip under the fault at 55 miles (78% total length) of transmission lines.

4.3 Performance under Varying Fault Resistance

AG faults are applied at 55 miles of L1 and L2 when t=2 s.

The fault resistance is set to 10 Ω, 15 Ω, and 17 Ω, respectively.

Figs. 8 and 9 show the ratio of $|\boldsymbol{I}_{Ga}|$ over $|\boldsymbol{I}_{Ma}|$ and the apparent impedance locus under the specified scheme (IBR1) and the conventional FRT scheme (IBR2).

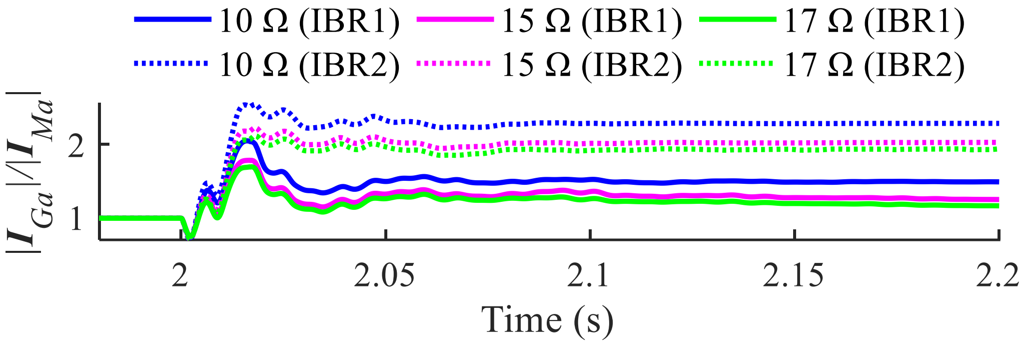

Fig. 8. Ratio of $|\boldsymbol{I}_{Ga}|$ over $|\boldsymbol{I}_{Ma}|$ under varying fault resistance

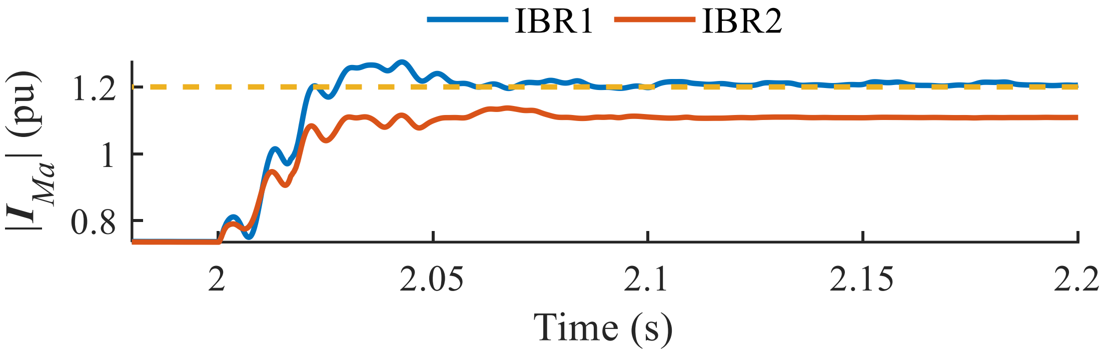

Fig. 9. Comparison of $|\boldsymbol{I}_{Ma}|$ under a 17 Ω fault resistance

From Fig. 8, the ratio of $|\boldsymbol{I}_{Ga}|$ over $|\boldsymbol{I}_{Ma}|$ under the conventional FRT scheme is higher than that under the specified scheme. The reason is that under fault steady state conditions, $|\boldsymbol{I}_{Ga}|$ can reach the maximum current limit by using the specified scheme, as shown in Fig. 9.

4.3 Performance under Varying Fault Resistance

Fig. 10 shows that with a 17 Ω fault resistance, the trajectory of apparent impedance under the conventional FRT scheme cannot enter zone 1, decreasing the sensitivity of distance protection. In contrast, the specified scheme enables zone 1 of protection to identify the fault correctly.

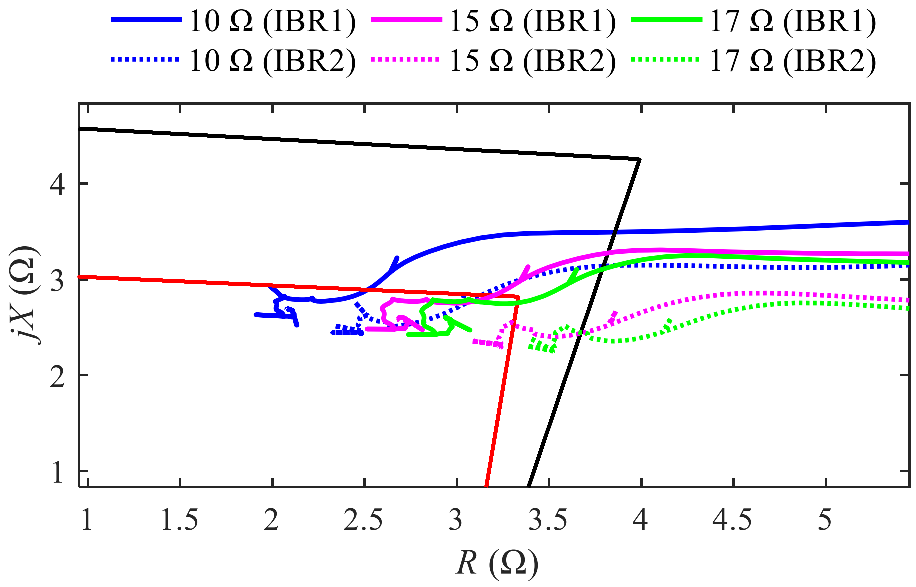

Fig. 10. Apparent impedance $\boldsymbol{Z}_M$ under varying fault resistance

4.4 Performance under Varying K factors

10 Ω AG faults are applied at 55 miles of L1 and L2 when t=2 s. The K factor for I1R injection (K^+) is set to 2, 4, and 6, respectively.

Figs. 11−13 show the current angle, reactive current injection, and the apparent impedance locus under the IBR1 and IBR2.

A larger K^+ results in a smaller current angle and a larger I1R injection.

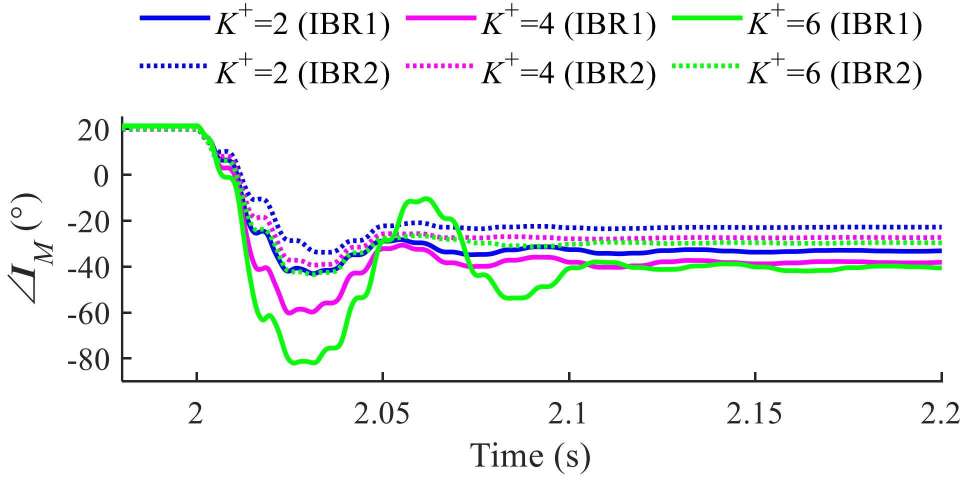

Fig. 11. Current angle $\measuredangle \boldsymbol{I}_{Ma}$ under varying K factor

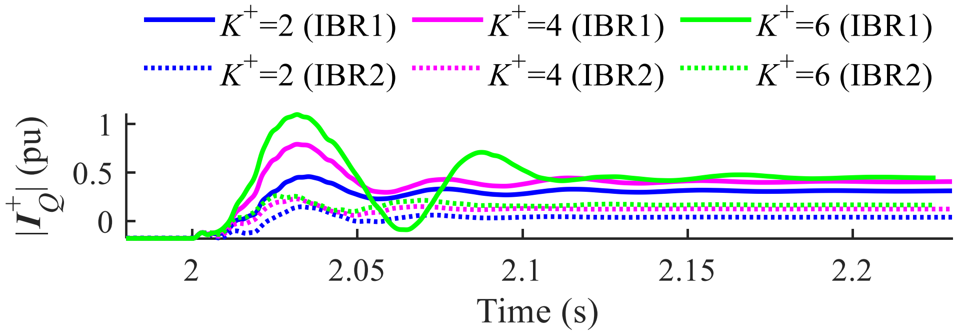

Fig. 12. I1R injection under varying K factor

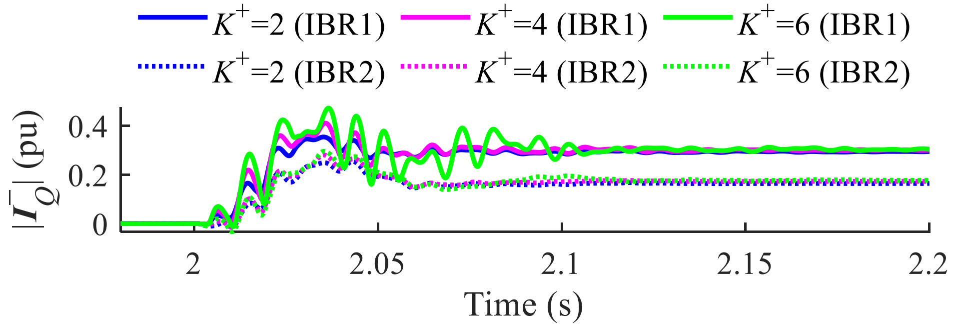

Fig. 13. I2R injection under varying K factor

4.4 Performance under Varying K factors

Moreover, since the specified scheme scales the phase current, there is a significant oscillation in waveforms when K^{+}=6, increasing the settling time, as shown in Fig. 14.

The IEEE 2800 requires a step response time of less than 2.5 cycles and a settling time of less than 4 cycles for the injected fault current of a fully sized converter unit. Hence, although the fault steady state current injection meets the IEEE 2800 when K^{+}=6, the dynamic performance fails to comply with IEEE 2800.

Figs. 15 and 16 show that the trajectory of apparent impedance shifts up as K^{+} increases, decreasing the speed of distance protection.

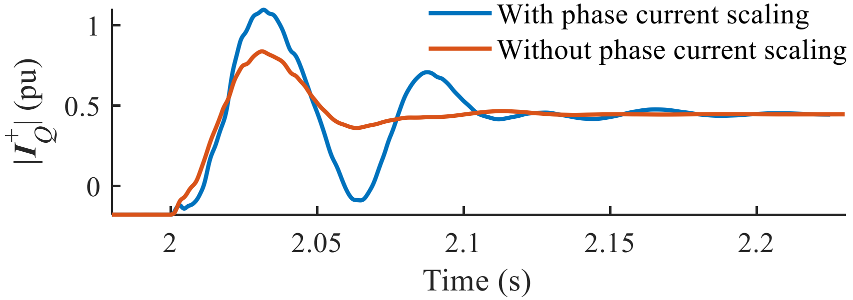

Fig. 14. Comparison of I1R injection of IBR1 when K^{+}=6

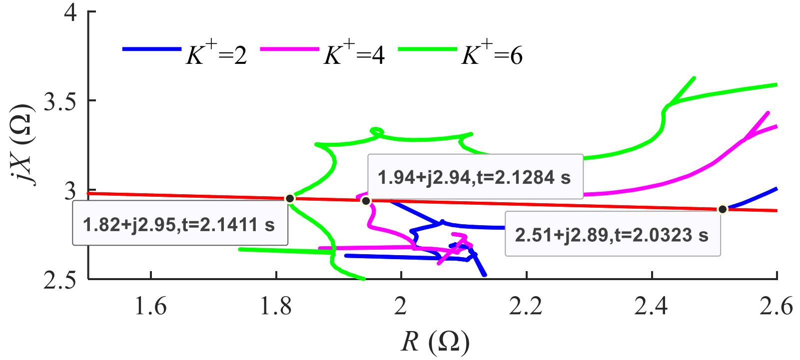

Fig. 16. Apparent impedance $\boldsymbol{Z}_M$ and crossover points of IBR1 under varying K factor

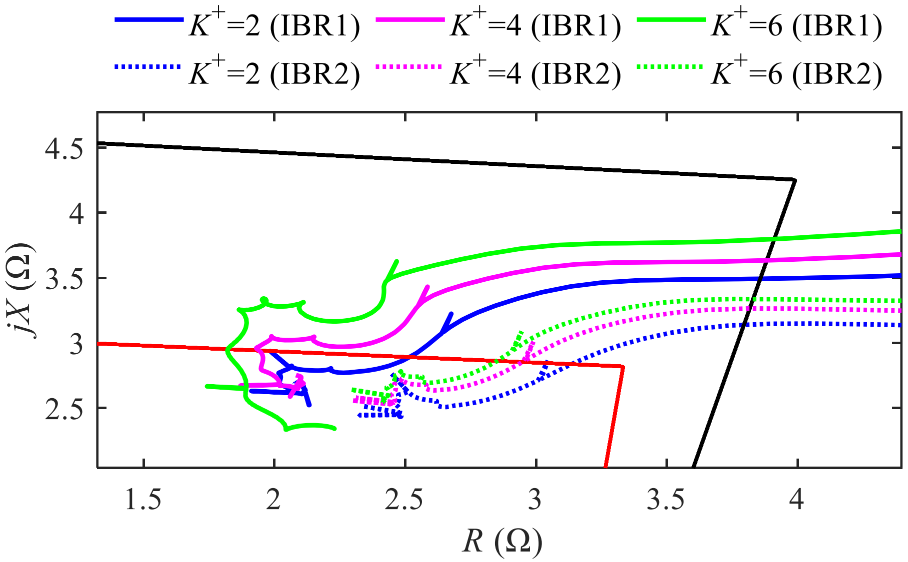

Fig. 15. Apparent impedance $\boldsymbol{Z}_M$ under varying K factor

5 Conclusion

The impacts of IEEE 2800 current injection requirements on distance protection are drawn as follows:

1. Per IEEE 2800 standard, IBRs shall be capable of injecting current to the maximum current limit. Hence, the ratio of $|\boldsymbol{I}_{Ga}|$ over $|\boldsymbol{I}_{Ma}|$ under the IEEE 2800-conforming FRT scheme is lower than that under the conventional FRT scheme, weakening the impacts of fault resistance on apparent impedance trajectory. Therefore, compared to the conventional FRT scheme, the trajectory of apparent impedance under the IEEE 2800-conforming FRT scheme is less sensitive to fault resistance, improving the sensitivity of distance protection.

2. The phase current scaling method in the IEEE 2800-conforming scheme FRT scheme causes an oscillation in waveforms when the K factor is large, increasing the settling time. Consequently, the trajectory of apparent impedance shifts up as the K factor increases, decreasing the speed of distance protection. Hence, the selection of K factors should be based on the converter current capacity to meet the dynamic performance requirement in IEEE 2800 and improve the speed of distance protection.

This paper focuses on the impacts of grid-following IBRs on distance protection. Future studies can include the grid code compliance control for grid-forming IBRs and their impacts on legacy protection.

Thanks