IMPERIAL

Protection Problem and Solution for IBR-dominated Power Systems

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- ❑ **Background**
- ❑ **Operating Challenges for Protection**
- ❑ **Active control-based Protection**

BACKGROUND

More and more renewable energy sources (RESs) are integrated into the power system to mitigate the environmental pollution. Benefited from policy support and technological progress, the supplied energy from RESs in UK increases rapidly.

British renewable source utilization:

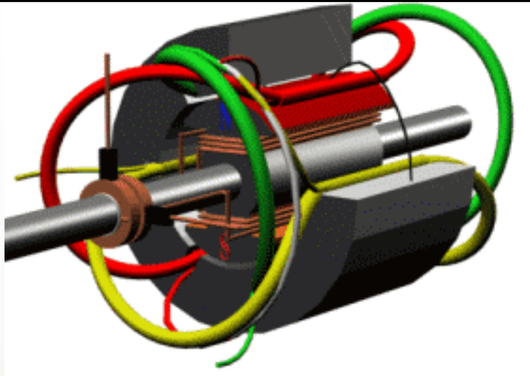
- Producing about 41% of all its energy needs from RE in 2025.
- Achieving 95% of the electricity from clear power in 2030.
- Reaching 100% of its energy needs from RE by 2050 (Net Zero).

Among them, inverter-based resources (IBRs) account for a big share. However, IBRs are connected to the power grid by power electronics, so IBRs will have different fault characteristics.

BACKGROUND

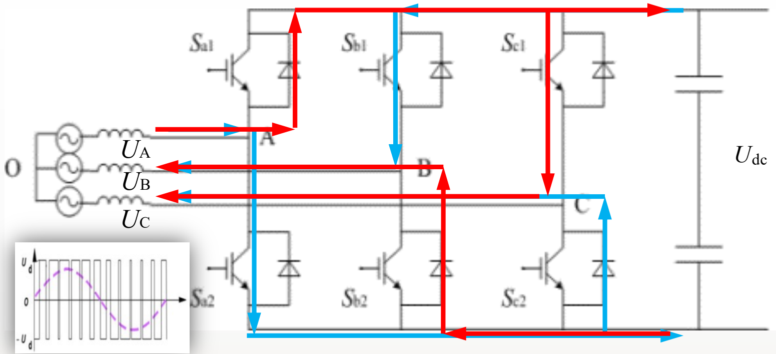
Compared with synchronous generators (SGs), IBRs show different fault behaviors.

SG



- Lasts for tens to hundreds of ms.
- Dozens of times the rated current.
- Stable sequence impedance angle.

IBR



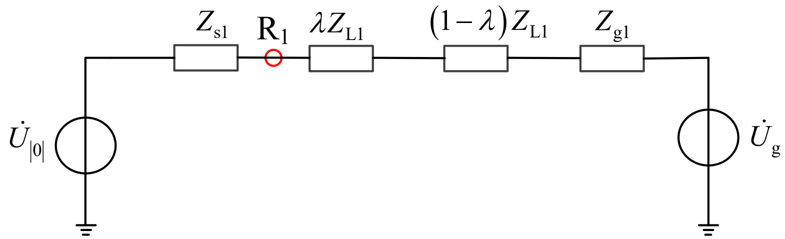
- Lasts for only 20 to 40 ms.
- The maximum is 1.2 to 1.5 times.
- Impedance varies from -180° to 180°.

These fault characteristics will threaten the correct operation of traditional protective relays since they are designed according to the fault behaviors of SGs.

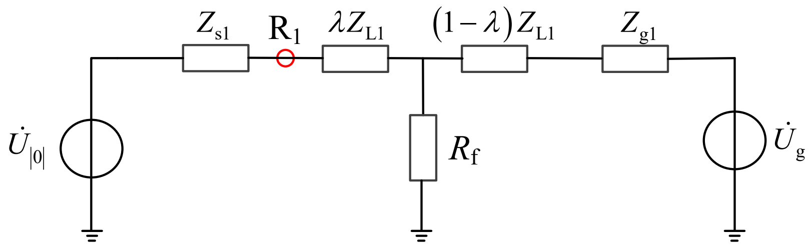
- Background
- **Operating Challenges for Protection**
- Active control-based Protection

Problem for Directional Relays

For SG-based power grid



Equivalent network before a fault



Equivalent network during a fault

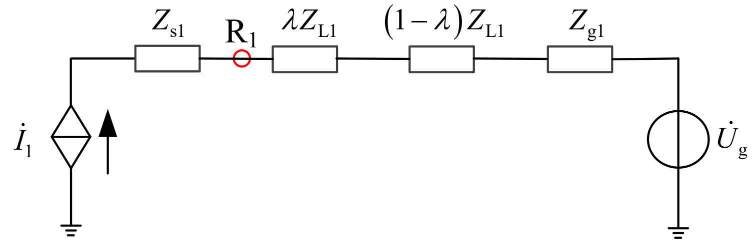
For relay point R1:

$$\Delta Z_1 = \frac{\Delta \dot{U}_1}{\Delta \dot{I}_1} = -Z_{s1}$$

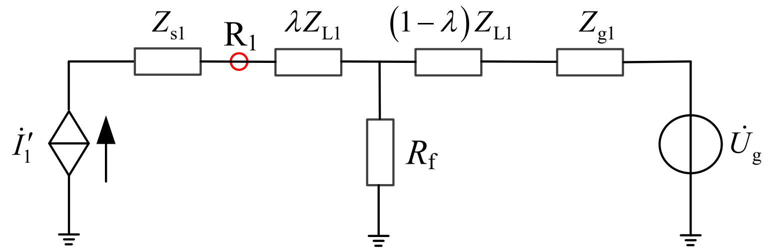
$$\Delta Z_2 = \frac{\Delta \dot{U}_2}{\Delta \dot{I}_2} = -Z_{s2}$$

Equal to the negative value of to the SG impedance!

For IBR-integrated power grid



Equivalent network before a fault



Equivalent network during a fault

For relay point R1:

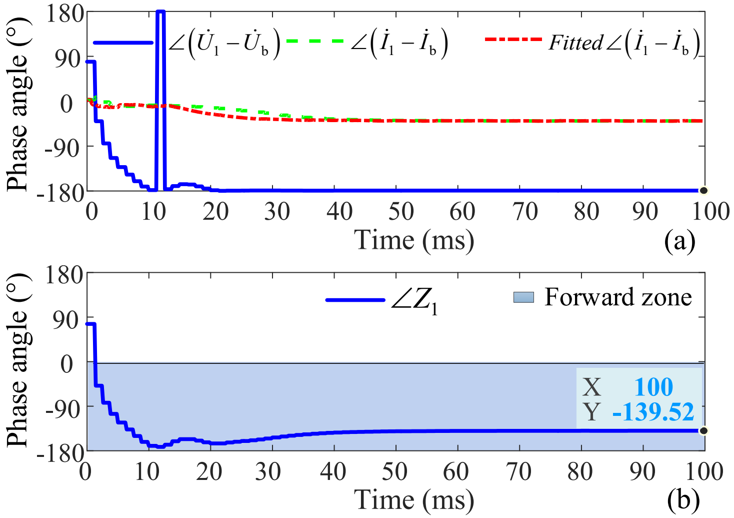
$$\Delta Z_1 = \frac{\Delta \dot{U}_1}{\Delta \dot{I}_1} = \frac{\Delta \dot{U}_1}{\dot{I}_1' - \dot{I}_1}$$

$$\Delta Z_2 = \frac{\Delta \dot{U}_2}{\Delta \dot{I}_2} = \frac{\Delta \dot{U}_1}{\dot{I}_2' - 0}$$

No definite physical meaning!

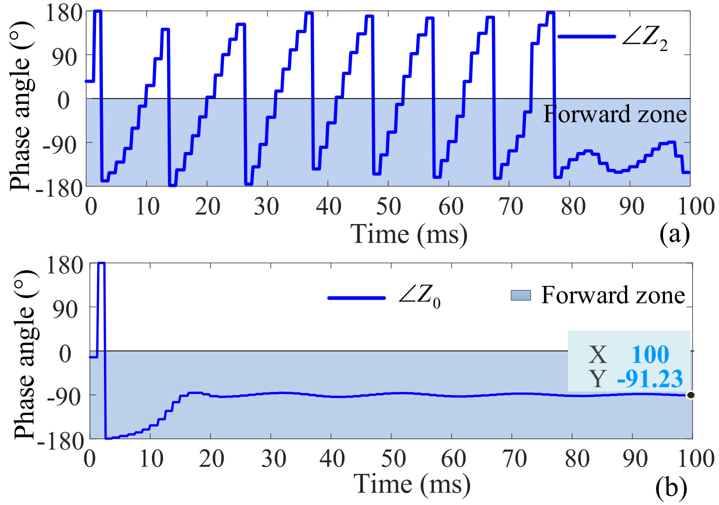
Problem for Directional Relays

Positive-sequence



The measured impedance angle for AG faults under Danish FRT

Negative- and zero-sequence



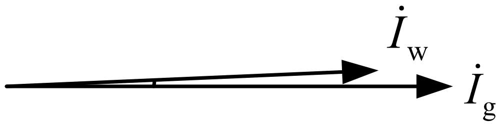
The measured impedance angle for AG faults under Danish FRT

1.The measured current of positive-sequence directional elements is controlled by current references.

2. Positive- and negative-sequence directional elements will be affected under Danish FRT, but zero-sequence directional elements is not affected since the zero-sequence fault loop does not include the IBR impedance.

Problem for Distance Relays

For SG-based power grid



Current phasors between both sides

- Similar current angles
- Similar current amplitudes

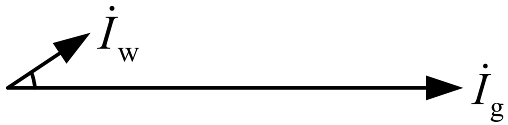
For apparent impedance at the relay point:

$$Z_{\mathrm{m}} = \frac{\dot{U}_{\mathrm{m}}}{\dot{I}_{\mathrm{m}}} = Z_{1\mathrm{k}} + R_{\mathrm{g}} + \underbrace{\frac{\dot{I}_{\mathrm{g}}}{\dot{I}_{\mathrm{w}}}}_{M_{\mathrm{abc}}} R_{\mathrm{g}}$$

Additional impedance

Due to the similar angle, the additional impedance is dominated by the resistive component, so a quadrilateral characteristic with a large resistive reach is often used.

For IBR-integrated power grid



Current phasors between both sides

- Large current angle difference
- Large current amplitude difference

For apparent impedance at the relay point:

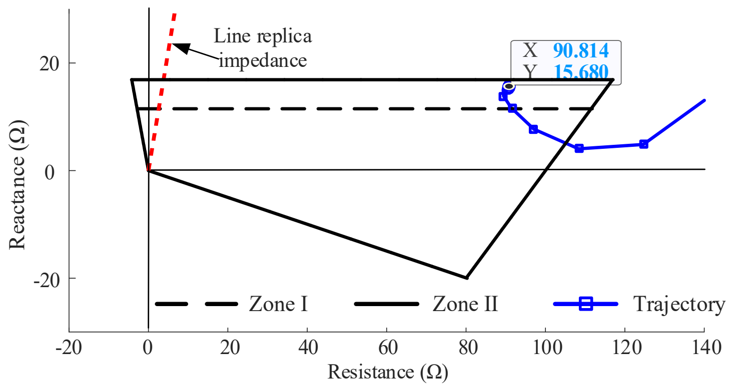
$$Z_{\mathrm{m}} = \frac{\dot{U}_{\mathrm{m}}}{\dot{I}_{\mathrm{m}}} = Z_{1\mathrm{k}} + R_{\mathrm{g}} + \underbrace{\frac{\dot{I}_{\mathrm{g}}}{\dot{I}_{\mathrm{w}}}}_{M_{\mathrm{abc}}} R_{\mathrm{g}}$$

Additional impedance

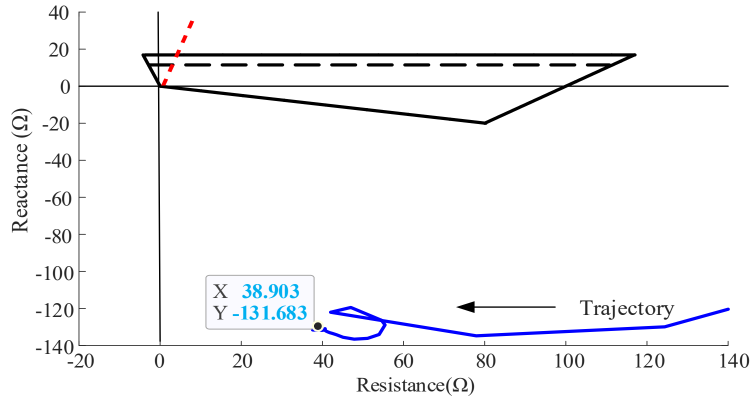
- The additional impedance has a large amplitude and present an inductive or capacitive feature.
- Original distance relays will fail to operate.

Problem for Distance Relays

A fault occurs at the midpoint of the line with 10 Ω of fault resistance



The performance for an AG fault under Danish FRT

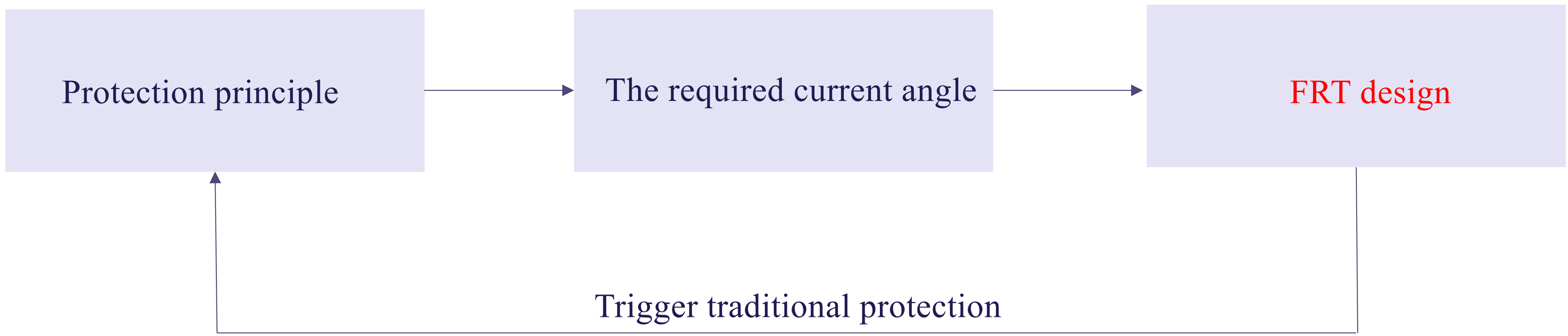


The performance for a BC fault under Danish FRT

- The impact of the IBR integration is not very large for AG fault due to zero-sequence current.
- Distance relay faces severe challenges for BC faults and ABCG faults.

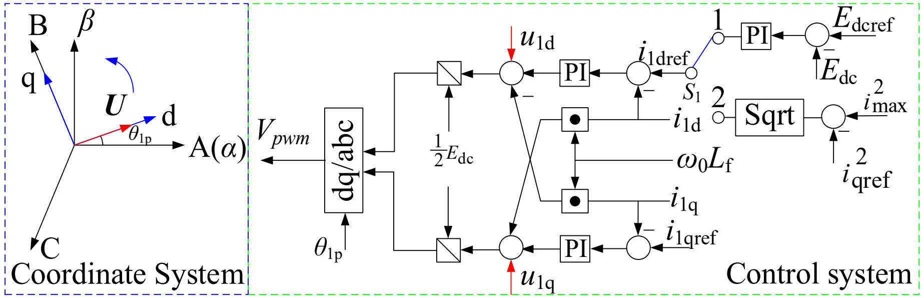
- ❑ Background
- ❑ Operating Challenges for Protection
- ❑ **Active control-based Protection**

Control-based solution

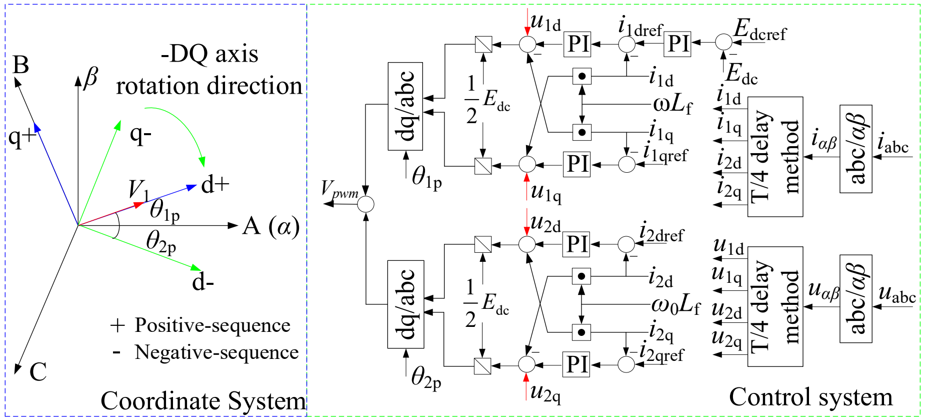


Core idea of control-based solution

The fault current of IBRs



Decoupled current control



Decoupled sequence control

Decoupled current control (DCC control): The fault current only includes the positive-sequence component:

$$i_{a1}=\sqrt{i_{1dref}^2+i_{1qref}^2}\,\sin\left(\omega_0 t+\theta_{1p}+\arctan\left(\frac{i_{1qref}}{i_{1dref}}\right)+90^\circ\right)$$

Phase-locked angle   Current command values

Decoupled sequence control (DSC control): Besides the positive-sequence component, it also includes the negative-sequence component:

$$i_{a2}=\sqrt{i_{2dref}^2+i_{2qref}^2}\,\sin\left(\omega_0 t-\theta_{2p}-\arctan\left(\frac{i_{2qref}}{i_{2dref}}\right)+90^\circ\right)$$

Control-based solution for directional relays

Since sequence fault currents of IBRs can be controlled, so we can set the suitable current references to make the measured impedance angle of positive- and negative-sequence directional elements restore to -90°.

Positive-sequence directional element

The measured impedance can be expressed as:

$$Z_1=\frac{|U_1|\cos\varphi_1-|U_b|\cos\varphi_b+\mathrm{j}\left(|U_1|\sin\varphi_1-|U_b|\sin\varphi_b\right)}{|I_1|\cos\alpha_1-|I_b|\cos\alpha_b+\mathrm{j}\left(|I_1|\sin\alpha_1-|I_b|\sin\alpha_b\right)}$$

$$\begin{cases}\boxed{\text{Angle: } \angle Z_1=\arctan\frac{B_1}{A_1}-\arctan\frac{B_2}{A_2}} \\ \text{Mag: } |Z_1|=\frac{\sqrt{\left(|U_1|\cos\varphi_1-|U_b|\cos\varphi_b\right)^2+\left(|U_1|\sin\varphi_1-|U_b|\sin\varphi_b\right)^2}}{\sqrt{\left(|I_1|\cos\alpha_1-|I_b|\cos\alpha_b\right)^2+\left(|I_1|\sin\alpha_1-|I_b|\sin\alpha_b\right)^2}}=\sqrt{\frac{A_1^2+B_1^2}{A_2^2+B_2^2}}\end{cases}$$

Make the impedance angle euqal to -90°:

$$\alpha_1=\arcsin\frac{F}{\sqrt{1+(\tan E)^2}}+E$$

$$\boxed{\begin{aligned}&E=\arctan\frac{B_1}{A_1}+90^\circ\\&F=\frac{|I_b|}{|I_1|}\sin\alpha_b-\frac{|I_b|}{|I_1|}\tan E\cdot\cos\alpha_b\end{aligned}}$$

Compared with the positive-sequence fault current expression:

$$i_{a1}=\sqrt{i_{1\mathrm{dref}}^2+i_{1\mathrm{qref}}^2}\sin\left(\omega t+\underbrace{\theta_{1\mathrm{p}}+\arctan\left(\frac{i_{1\mathrm{qref}}}{i_{1\mathrm{dref}}}\right)+90^\circ}_{\alpha_1}\right)$$

The first constraint for current references:

$$\begin{cases}\boxed{k_1=\frac{i_{1\mathrm{qref}}}{i_{1\mathrm{dref}}}=\tan\left(\alpha_1-90^\circ-\theta_{1\mathrm{p}}\right)} \\ I_{1\mathrm{m}}=\sqrt{i_{1\mathrm{dref}}^2+i_{1\mathrm{qref}}^2}\end{cases}\Rightarrow\begin{cases}i_{1\mathrm{dref}}=\sqrt{\frac{1}{1+k_1^2}}I_{1\mathrm{m}}\\ i_{1\mathrm{qref}}=k_1 i_{1\mathrm{dref}}\end{cases}$$

Unknown

Control-based solution for directional relays

The measured impedance angle of negative-sequence directional elements can be also adjusted in a similar way. In addition, the short circuit capacity can be fully utilized by an iterative method.

Negative-sequence directional element

The measured impedance angle is:

$$Z_2 = \frac{|U_2|}{|I_2|} \angle(\varphi_2 - \alpha_2)$$

Impedance angle

Make this impedance angle equal to -90°:

$$\alpha_2 = \varphi_2 + 90^\circ$$

Constraints for current references:

$$\begin{cases} k_2 = \dfrac{i_{2\text{qref}}}{i_{2\text{dref}}} = -\tan\left(\varphi_2 + \theta_{2\text{p}}\right) \\ I_{2\text{m}} = \sqrt{i_{2\text{dref}}^2 + i_{2\text{qref}}^2} \end{cases}$$

Unknown

The required current references:

$$\begin{cases} i_{2\text{dref}} = \sqrt{\dfrac{1}{1+k_2^2}} I_{2\text{m}} \\ i_{2\text{qref}} = k_2 i_{2\text{dref}} \end{cases}$$

Positive- and negative-seq distribution

At first, using scalar sum to distribute

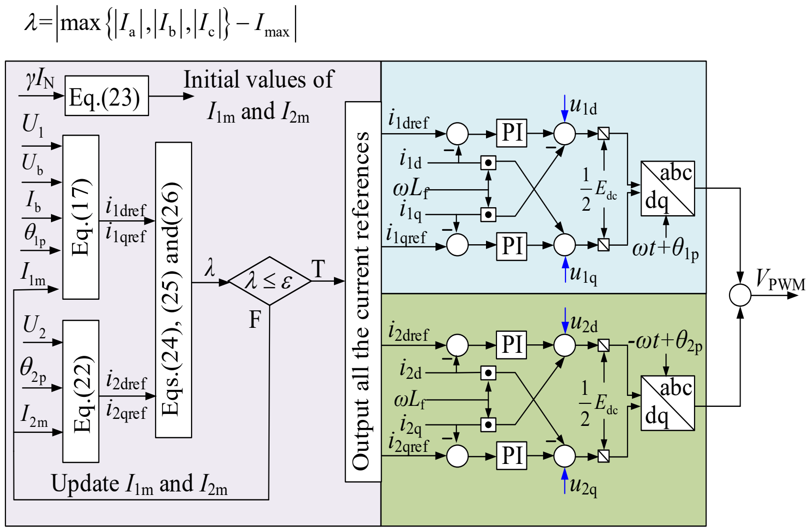
$$I_{\max} = |I_1| + |I_2| = (1+\beta)|I_1|$$

However, the phase current should be the phasor sum, so the short-circuit capacity is not fully used. To solve this problem, First, the relationship between three-phase current and sequence currents:

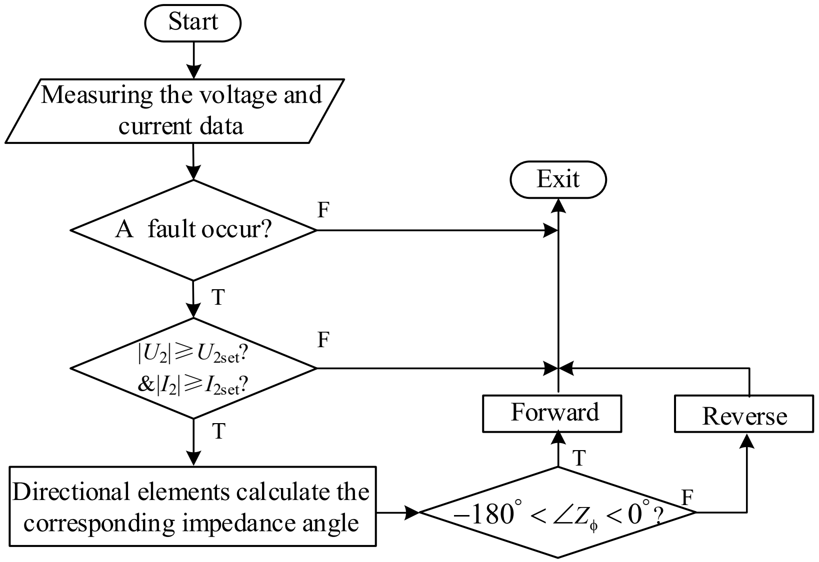
$$\begin{cases} |I_a| = \sqrt{|I_1|^2 + |I_2|^2 + 2|I_1||I_2|\cos\Delta\alpha} \\ |I_b| = \sqrt{|I_1|^2 + |I_2|^2 - 2|I_1||I_2|\cos(\Delta\alpha - 60^\circ)} \\ |I_c| = \sqrt{|I_1|^2 + |I_2|^2 - 2|I_1||I_2|\cos(\Delta\alpha + 60^\circ)} \end{cases}$$

Then an iterative algorithm is proposed.

Control-based solution for directional relays



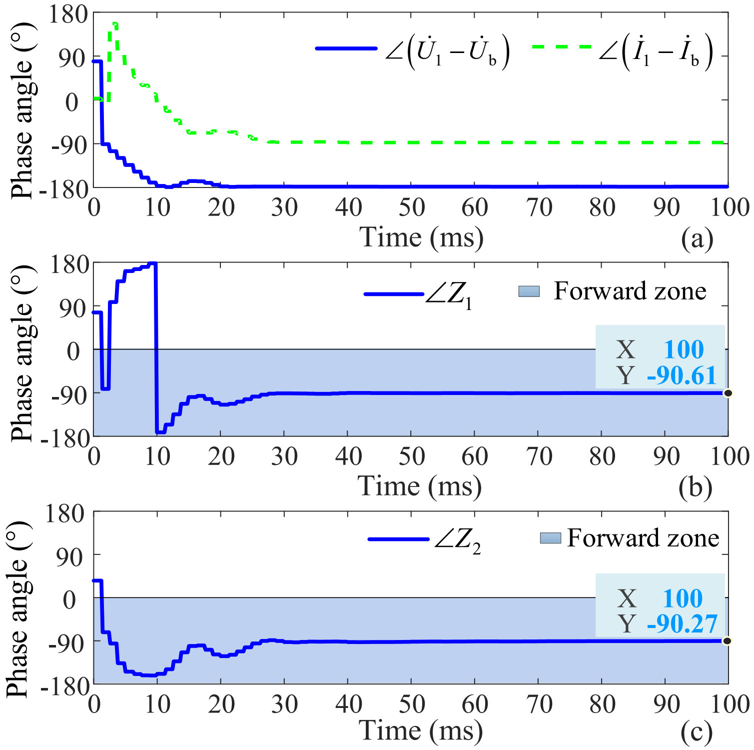
The proposed control scheme



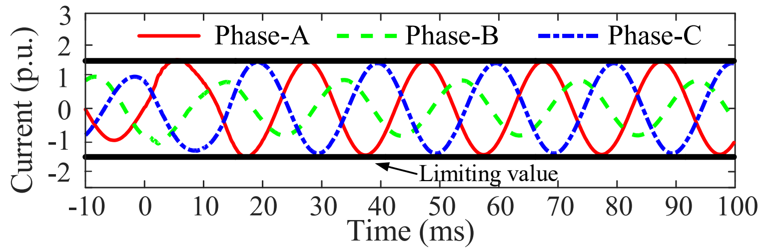
Protection flowchart

After the inverter detect a fault, the IBR will perform the proposed FRT control, and then the relay can determine the fault direction correctly.

Control-based solution for directional relays



The measured current and the impedance angle for AG faults under the proposed control. (a) current, (b) positive-sequence, (c) negative-sequence

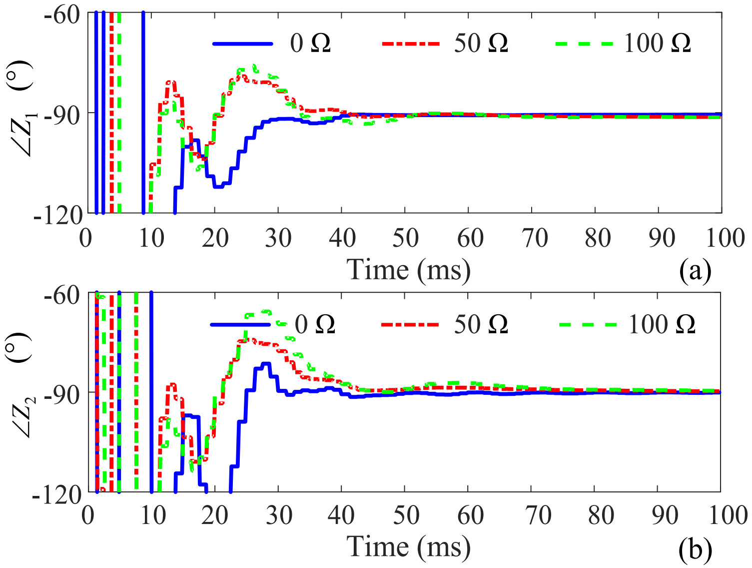


The output three-phase fault currents under the proposed control

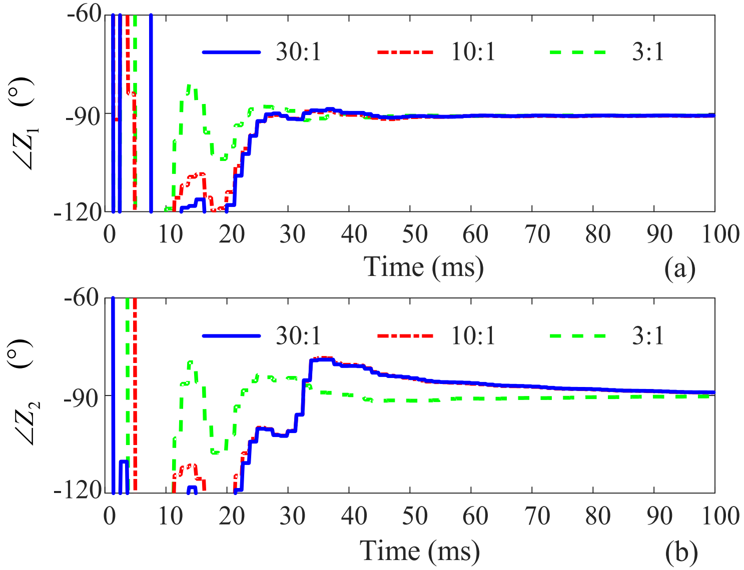
- The measured current angle of directional elements can be adjusted according to the measured voltage, so the measured impedance angle is restored to -90°.
- The maximum value of three-phase fault currents can reach the current limiting value.

Control-based solution for directional relays

Fault resistance



Short circuit ratio



The measured impedance angle is always close to -90°, so the proposed control method can make directional elements operate properly under different fault resistances and different short circuit ratios.

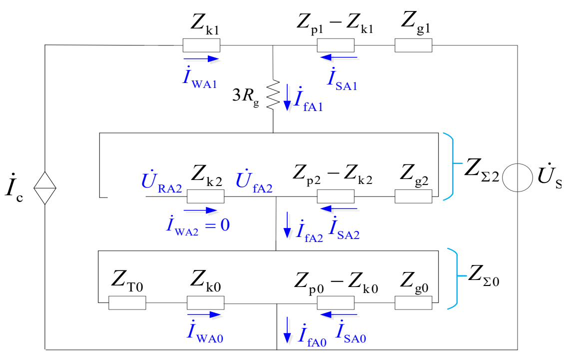
Control-based solution for distance relays

If the phase angle of M_{ag}, M_{bc} and M_{bcg} can be controlled to 0°, the additional impedance will be a purely resistive component, so the apparent reactance will be equal to the line fault reactance.

$$Z_{bc} = Z_{k1} + \underbrace{\left(\frac{\dot{I}_{WB} + \dot{I}_{SB}}{\dot{I}_{WB} - \dot{I}_{WC}}\right)}_{M_{bc}} R_g$$

$$X_{bc} = X_{k1}$$

Purely resistive component



Sequence network diagram for AG faults

AG faults

Sequence currents for AG faults should satisfy:

$$\begin{cases} \dot{I}_{fA1} = \dot{I}_{WA1} + \dot{I}_{SA1} \\ \dot{I}_{fA2} = \dot{I}_{SA2} \\ \dot{I}_{fA0} = \dot{I}_{WA0} + \dot{I}_{SA0} \end{cases}, \quad \dot{I}_{fA1} = \dot{I}_{fA2} = \dot{I}_{fA0}$$

Substitute it into the expression of M_{ag}:

$$M_{ag} = \frac{\dot{I}_{fA1} + \dot{I}_{fA2} + \dot{I}_{fA0}}{\dot{I}_{WA1} + (1 + k_0 \cdot 3)\dot{I}_{WA0}} = \frac{3\dot{I}_{SA2}}{\dot{I}_{WA1} + (1 + k_0 \cdot 3)\dot{I}_{WA0}}$$

We can obtain the required current angle:

$$\angle \dot{I}_{WA1} = \angle \dot{I}_{SA2}$$

$\angle \dot{I}_{SA2}$ can be calculated by:

$$\angle \dot{I}_{SA2} = \angle \dot{U}_{RA2} - \angle Z_{SL2} + 180^{\circ}$$

Control-based solution for distance relays

The required current angle for BC and BCG faults can be obtained in a similar way, so here it is not repeated. In this part, the corresponding control strategy will be designed to make IBRs generate the required current angle.

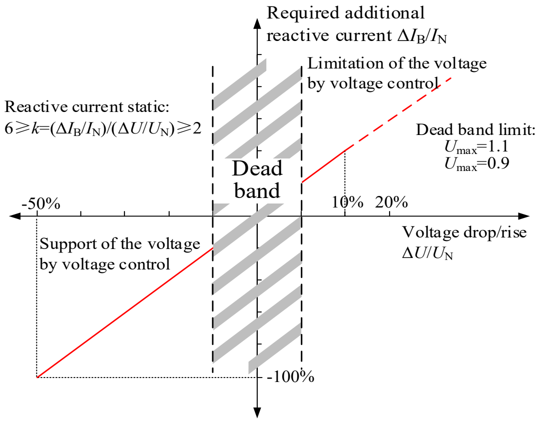
DCC control

To generate this required current angle, the first constraint for current references can be obtained:

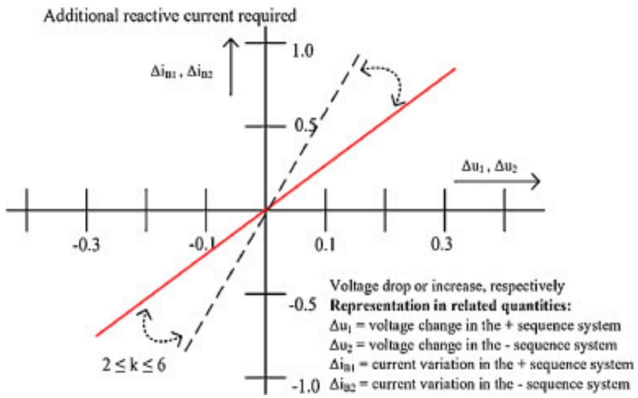
$$I_{1\mathrm{dref}} = \frac{I_{1\mathrm{qref}}}{\tan(\angle \dot{I}_{\mathrm{WA1}} - \theta_{1\mathrm{v}} - 90^{\circ})}$$

After that, $I_{1\mathrm{qref}}$ will be given according to the grid code, and then, they are scaled down to prevent overcurrent:

$$\begin{cases} I'_{1\mathrm{dref}} = I_{1\mathrm{dref}} / N \\ I'_{1\mathrm{qref}} = I_{1\mathrm{qref}} / N \end{cases}, \quad N = \max\left(1, \frac{\sqrt{I_{1\mathrm{dref}}^2 + I_{1\mathrm{qref}}^2}}{\eta}\right)$$



Grid code for the DCC control



Grid code for the DSC control

DSC control

To generate this required negative-sequence current angle, the first constraint for current references can be obtained:

$$I_{2\mathrm{dref}} = \frac{I_{2\mathrm{qref}}}{\tan(-\theta_{2\mathrm{v}} + 90^{\circ} - \angle \dot{I}_{\mathrm{WA2}})}$$

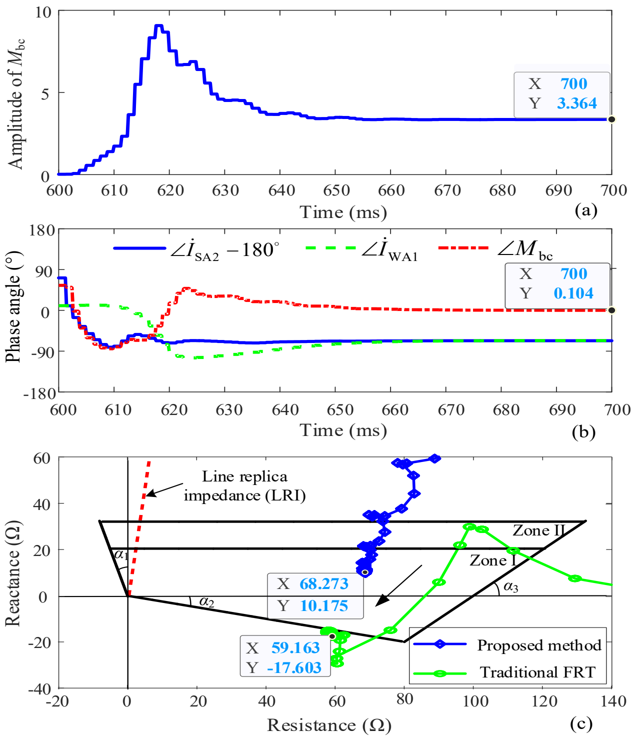
All the current references must be scaled down to prevent overcurrent:

$$\begin{cases} I'_{1\mathrm{dref}} = I_{1\mathrm{dref}} / M, & I'_{1\mathrm{qref}} = I_{1\mathrm{qref}} / M \\ I'_{2\mathrm{dref}} = I_{2\mathrm{dref}} / M, & I'_{2\mathrm{qref}} = I_{2\mathrm{qref}} / M \end{cases}$$

$$M = \max\left(1, \frac{\sqrt{\left(\left|I_{1\mathrm{dref}}\right| + \left|I_{2\mathrm{dref}}\right|\right)^2 + \left(\left|I_{1\mathrm{qref}}\right| + \left|I_{2\mathrm{qref}}\right|\right)^2}}{\eta}\right)$$

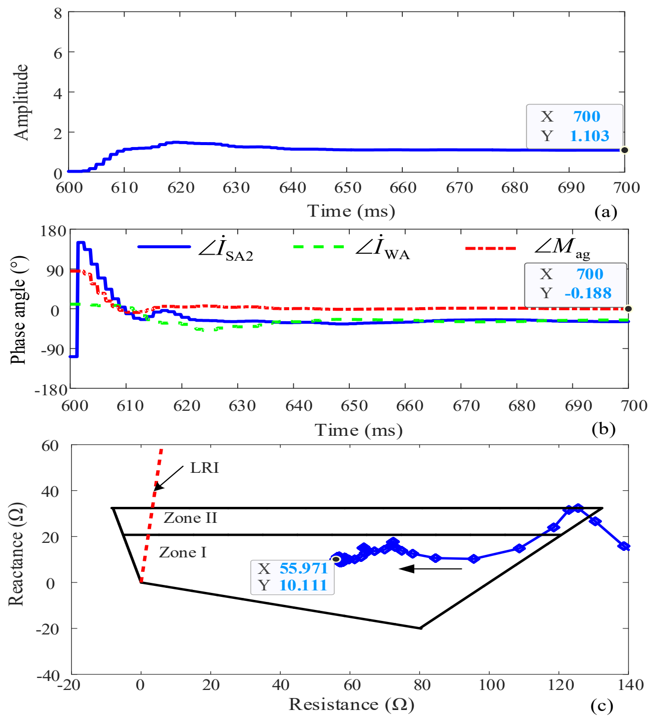
Control-based solution for distance relays

DCC



The amplitude and angle of M_{bc} and the apparent impedance

DSC



The amplitude and angle of M_{ag} and the apparent impedance

We can see that the phase angle of M_{bc} and M_{ag} can be controlled to 0°, so the apparent reactance of distance relays is close to the line fault reactance of 10.368 Ω regardless of DCC control or DSC control.

References

[1] Z. Yang, Z. Liu, Q. Zhang, Z. Chen, J. d. J. Chavez and M. Popov, "A Control Method for Converter-Interfaced Sources to Improve Operation of Directional Protection Elements," in *IEEE Transactions on Power Delivery*, vol. 38, no. 1, pp. 642-654, Feb. 2023.

[2] Z. Yang, W. Liao, Q. Zhang, C. L. Bak and Z. Chen, "Fault Coordination Control for Converter-Interfaced Sources Compatible With Distance Protection During Asymmetrical Faults," in IEEE Transactions on Industrial Electronics, vol. 70, no. 7, pp. 6941-6952, July 2023.

THANK YOU!