Improved Fault Phase Selection Scheme for Lines Terminated by Inverter Based Resources

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***Abstract*—With more renewable energy integrated to the grid in the form of inverter based resources (IBRs), traditional current-based fault phase selector encounters limitations. The causes of this problem are the weak infeed feature and variation of source impedance of IBRs. This paper proposes an improved fault phase selection scheme to solve this problem. Firstly, the reasons for the failure of traditional fault phase selection methods are analyzed. Then, compound proportion criterion including voltages and currents is established. The proposed criterion mitigates the effects of the weak-infeed feature and source impedance variation caused by IBRs. Finally, the corresponding improved phase selection method is proposed. The main advantages of proposed method are excellent adaptability and reliability. Numerical experiments prove the effectiveness of the proposed method.**

***Index Terms*-- Fault phase selector, transmission line, inverter based resources (IBRs), asymmetrical faults, weak-infeed circuit**

I. INTRODUCTION

Phase selector is a key component of the protective relay, and its correct operation builds the foundation for automatic reclosing, protection, and fault location [1-2]. Nowadays, an increasing number of renewables are integrated to the grid in the form of inverter based resources (IBRs) [3-4]. The fault current characteristics of IBRs are quite different from those of synchronous generators. These factors present challenges to traditional protective relay systems, including fault phase selectors [5-6].

Fault phase selection methods can be divided into three categories. Fault phase selection based on phasors is a mature technology with many improvements [7-11]. Methods based on transient characteristics are preliminarily verified in [12-13]. Another group of potential approaches are data-driven methods based on machine-learning [14]. Current-based phasor schemes are the most widely used fault selection method in the power gird [7-8]. These methods are designed for the grid where the line and source impedances are approximately homogeneous. However, the output characteristics of IBRs include weak infeed feature, variation of equivalent source impedance and non-homogeneity [15]. Hence, the traditional phase selection methods have reliability problem in lines terminated by IBRs [12].

To mitigate the effects of IBRs, some improvements on traditional power frequency phasor based methods are proposed. A current-based method with angle correction [8] optimizes the accuracy of phase selection. It needs the equivalent impedance of remote system that is not easy to acquire in real-time. References [9] uses voltage criterion instead of current criterion to adapt the weak infeed source, but the variation of source impedance of IBRs is not considered. In [10], an improved method based on voltage criterion is presented, which relies on the assumptions that IBRs do not inject negative sequence current. In addition, reference [11] mentions an improved control scheme of inverter that make traditional phase selection method work correctly. This method requires adjustments of inverters. The aforementioned methods improve the performances of phase selection element, but also require the system to meet specific conditions such as specific control strategy or availability of extra data.

In this paper, an improved scheme of fault phase selector is proposed for lines terminated by IBRs. This method is based on the phasor measurements and does not require extra data. Session II analyses the impact of IBR and theoretically explains why existing phase selection elements cannot work. In Session III, the paper derives the analytical expressions of the fault current components without local source impedance. Next, a compound proportion criterion based on the local voltage component and current component is established, and the phase angle characteristics of the criterion for different faults are discussed respectively. Finally, the phase selector is designed based on the proposed criterion. Section IV carries out numerical experiments to validate the performances of the proposed method, with comparison to two existing methods. The proposed method can accurately distinguish fault types for lines with IBRs and it is adaptive to different inverter control schemes. Section V concludes the paper.

II. CHALLENGES OF TRADITIONAL PHASE SELECTORS

A. Traditional Current-Based Phase Selection Method

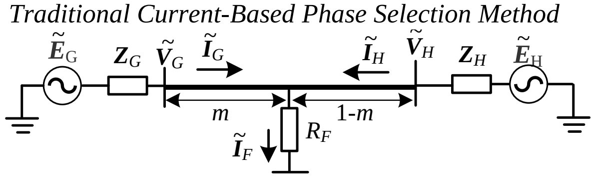

Fig. 1 An example two-terminal transmission line with fault

The basic principle of traditional phase selection method is the fault analysis based on sequence network [7]. The main criteria of traditional phase selection method are defined as $\alpha = \arg(\tilde{I}_0 / \tilde{I}_2)$ and $\beta = \arg(\Delta\tilde{I}_1 / \tilde{I}_2)$ [8]. The subscripts 0, 1 and 2 correspond to zero, positive and negative sequence components, and the operator Δ means the difference of the physical quantities before and during the fault.

As shown in Fig.1, an asymmetrical fault occurs on a transmission line in the conventional grid without IBRs, and the phase selector is installed at G side. According to the current distribution theory, the fault current components satisfy the following equations,

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$$\begin{cases} \dfrac{\Delta\tilde{I}_{G1}}{\tilde{I}_{F1}} = \dfrac{Z_{H1}+(1-m)Z_{L1}}{Z_{G1}+Z_{H1}+Z_{L1}} \\ \dfrac{\tilde{I}_{G2}}{\tilde{I}_{F2}} = \dfrac{Z_{H2}+(1-m)Z_{L2}}{Z_{G2}+Z_{H2}+Z_{L2}} \\ \dfrac{\tilde{I}_{G0}}{\tilde{I}_{F0}} = \dfrac{Z_{H0}+(1-m)Z_{L0}}{Z_{G0}+Z_{H0}+Z_{L0}} \quad \text{(For grounded fault)} \end{cases} \tag{1}$$

For synchronous generators, the phase angles of line impedances are close to that of the source equivalent impedances, for positive, negative and zero sequence values. In this case, the system is almost homogeneous. Therefore, the angles of the three proportions on the right side of (1) are all approximately 0 degrees,

$$\arg\left(\frac{\Delta\tilde{I}_{G1}}{\tilde{I}_{F1}}\right) = \arg\left(\frac{\tilde{I}_{G2}}{\tilde{I}_{F2}}\right) \approx \arg\left(\frac{\tilde{I}_{G0}}{\tilde{I}_{F0}}\right) \approx 0° \tag{2}$$

Based on the relationship among sequence currents (due to the connection of sequence networks during different types of faults), such as $\tilde{I}_{F1} = \tilde{I}_{F2} = \tilde{I}_{F0}$ for A-G faults and $\tilde{I}_{F1}e^{j120°} = -\tilde{I}_{F2}e^{-j120°}$ for A-B faults, the phase angles α and β of the current proportion can be determined for different fault types. For example, for A-G fault, the result is,

$$\begin{aligned} \alpha &= \arg(\tilde{I}_{G0}/\tilde{I}_{G2}) = 0° \\ \beta &= \arg(\Delta\tilde{I}_{G1}/\tilde{I}_{G2}) = 0° \end{aligned} \tag{3}$$

All the criteria of above methods are shown in Table I. In general, angle margins of $\pm 60°$ are set to avoid the impact of measurement noises and nonhomogeneous systems. This method has good performances in conventional grids. A series of improved methods such as phase current fault components based methods are also from this principle [8].

Table I. Criteria of traditional phase selection method

Fault type	α	β	**Other features**
AG	0 °	0 °	—
BG	120 °	-120 °	—
CG	-120 °	120 °	—
BCG	0 °	180 °	—
CAG	120 °	60 °	—
ABG	-120 °	-60 °	—
BC	—	180 °	$\tilde{I}_0 = 0$
CA	—	60 °	
AB	—	-60 °	
ABC\ABCG	—	—	$\tilde{I}_0 = \tilde{I}_2 = 0$

B. The Impact of IBRs on Phase Selection Elements

Consider an IBR connecting to the left bus of the transmission line. The equivalent model is shown in Fig. 2. The characteristics of the IBR model is different from the synchronous generator model. For synchronous generators, the equivalent source voltage and internal source impedance can be treated as constants during line faults. However, for IBRs, the equivalent source voltage and internal source impedance could vary during line faults due to the control strategy of the inverter.

For instance, the output current of IBR using PQ control in Fig. 3 is determined by the reference current. The reference current in this scheme depends on the port voltage, the complex power setting and the maximum current limit. IBR is treated as a controlled current source when it is connected to main-grid [5].

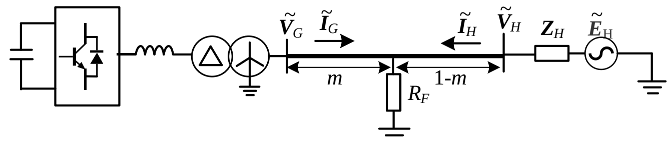

Fig. 2 Transmission line with IBR connected to local terminal

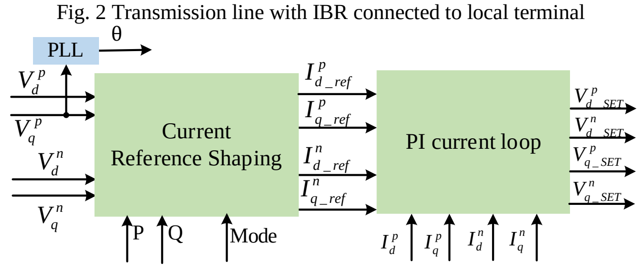

Fig. 3 The main part of PQ control

The characteristics of IBR bring the following influences on the existing phase selection methods:

1) Local terminal cannot be equivalent to a source with fixed internal impedance (zero sequence is the exception because of *dYN* step-up transformer on the output interface). Since the positive and negative sequence components are controlled separately, the phase angles of the three current ratios in (1) are generally far from 0 °. This means that equation (2) no longer holds, which is the basis for the traditional selection method. In fault cases, the offset of angles may exceed the margins of the criteria, resulting in incorrect phase selection result.

2) Some control of IBRs keeps zero negative sequence output current when the asymmetric fault occurs [16]. If $\tilde{I}_{G2}$ is close to 0, the results calculated by (3) is unreliable because the denominator is too small. The existing method cannot get stable phase selection results in this case.

There are some existing improved phase selection schemes for IBRs assuming that the negative sequence output current is small enough. However, Chinese and North American grid codes do not stipulate the level of negative sequence currents during asymmetrical faults [17]. This fact affects the reliability of existing improved methods.

To sum up, traditional phase selection method is not adaptive for the system with IBRs due to variable source impedance and negative sequence current characteristics.

III. Proposed Method

A. Expressions of Fault Currents

An asymmetric fault occurs at distance *m*, and the fault equivalent sequence circuit is shown in Fig. 4. The grid side is dominated by synchronous generators. In this case, $\tilde{E}_H$ can be treated as a constant before and during the fault.

From the Kirchhoff's Voltage Law (KVL) at terminal G,

$$\begin{aligned} \Delta\tilde{V}_{G1} &= (\Delta\tilde{V}_{G1} - \Delta\tilde{V}_{F1}) + (\Delta\tilde{V}_{F1} - \Delta\tilde{E}_H) + \Delta\tilde{E}_H \\ &= \Delta\tilde{I}_{G1} m Z_{1L} - \Delta\tilde{I}_{H1}[(1-m)Z_{1L} + Z_{H1}] + 0 \end{aligned} \tag{4}$$

From the Kirchhoff's Current Law (KCL) at the fault point,

$$\Delta\tilde{I}_{H1} + \Delta\tilde{I}_{G1} - \tilde{I}_{F1} = 0 \tag{5}$$

Thus, (4) can be expressed as follow,

$$\Delta\tilde{V}_{G1} = \Delta\tilde{I}_{G1} m Z_{1L} - (\tilde{I}_{F1} - \Delta\tilde{I}_{G1})[(1-m)Z_{1L} + Z_{H1}] \tag{6}$$

The positive sequence fault current can be estimated as,

$$\tilde{I}_{F1} = \frac{-\Delta\tilde{V}_{G1} + \Delta\tilde{I}_{G1}(Z_{1L} + Z_{H1})}{(1-m)Z_{1L} + Z_{H1}} \tag{7}$$

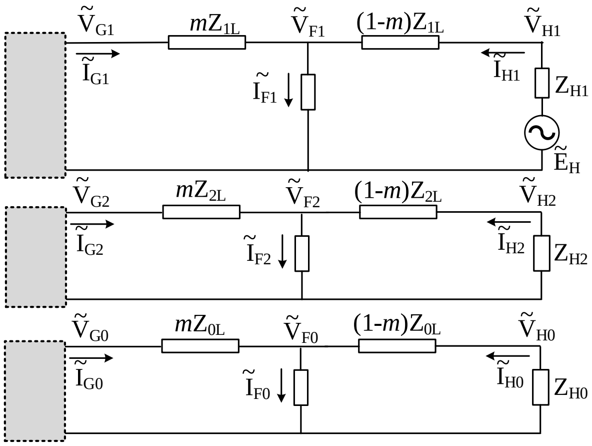

Fig. 4 The fault equivalent sequence circuit

Similar expressions can be obtained for the negative sequence fault current components. The expression is,

$$\tilde{I}_{F2}=\frac{-\tilde{V}_{G2}+\tilde{I}_{G2}(Z_{2L}+Z_{H2})}{(1-m)Z_{2L}+Z_{H2}} \tag{8}$$

For A-G faults, the relationship between fault current components still holds,

$$\tilde{I}_{F1}=\tilde{I}_{F2}=\tilde{I}_{F0} \tag{9}$$

The equation of (7) to (9) establishes the relationship between fault current components that does not depend on the control strategies of IBRs.

B. Phase Selection Criterion and Angle Characteristics

(1) Single phase to ground (SPG) faults

Take A-G faults as examples. From (7) to (8), the phase angle differences between the positive and negative sequence fault currents can be calculated as (10). From (9), the result of (10) should be zero degree. For further simplification, since the line and grid (H) side impedances of positive and negative sequence are equal, the two denominator terms with *m* are cancelled out,

$$\arg(\frac{\tilde{I}_{F1}}{\tilde{I}_{F2}})=\arg(\frac{-\Delta\tilde{V}_{G1}+\Delta\tilde{I}_{G1}(Z_{1L}+Z_{H1})}{-\tilde{V}_{G2}+\tilde{I}_{G2}(Z_{2L}+Z_{H2})})=0^\circ \tag{10}$$

Define the expression as criterion δ,

$$\delta=\arg(\frac{-\Delta\tilde{V}_{G1}+\Delta\tilde{I}_{G1}(Z_{1L}+Z_{H1})}{-\tilde{V}_{G2}+\tilde{I}_{G2}(Z_{1L}+Z_{H2})}) \tag{11a}$$

For transmission lines connecting IBRs to the power grid, the internal impedances of the power grid could be rather small due to the large scale of the grid, i.e., Z_{H1} and Z_{H2} are rather small in comparison to Z_{1L}. In this case, the terms of the grid side impedances in (11a) can be neglected, i.e.,

$$\delta=\arg(\frac{-\Delta\tilde{V}_{G1}+\Delta\tilde{I}_{G1}Z_{1L}}{-\tilde{V}_{G2}+\tilde{I}_{G2}Z_{1L}}) \tag{11b}$$

From (10) and the definition of δ, $\delta\approx 0^\circ$ for A-G faults. From the symmetry of three phase systems, the value of δ is close to -120° for B-G faults due to $\tilde{I}_{F1}e^{-j120^\circ}=\tilde{I}_{F2}e^{j120^\circ}$ and is 120° for C-G faults.

From (11b), this criterion only uses line parameters and local measurements that can be easily obtained, making the criterion practical for field applications. Since it includes both voltage and current data, it is referred as the "compound proportion criterion". Note that if the values of Z_{H1} and Z_{H2} are available, they can be substituted into the expression in (11a) to further improve the accuracy of δ.

The derivations of (7) to (11) do not assume the control strategies of IBRs. For example, the compound proportion criterion holds for IBRs restraining or not restraining negative-sequence currents.

(2) Phase to phase (PP) faults

During phase to phase faults, the zero sequence component is 0. The relationship between fault current positive and negative components during B-C faults is $\tilde{I}_{F1}=-\tilde{I}_{F2}$. Similarly, the angle δ can be derived as follows,

$$\delta\approx\arg(\frac{-\Delta\tilde{V}_{G1}+\Delta\tilde{I}_{G1}(Z_{1L}+Z_{H1})}{-\tilde{V}_{G2}+\tilde{I}_{G2}(Z_{1L}+Z_{H1})})=\arg(\frac{\tilde{I}_{F1}}{\tilde{I}_{F2}})=180^\circ \tag{12}$$

Therefore, if the criterion δ is defined as (11), it is close to 180° during B-C faults. Similarly, it is close to 60° for C-A faults and -60° for A-B faults.

(3) Double phase to ground (PPG) faults

For B-C-G faults, the KCL equation at the fault point is,

$$\tilde{I}_{F1}=-(\tilde{I}_{F2}+\tilde{I}_{F0}) \tag{13}$$

Equation (13) cannot directly obtain the corresponding angle of compound proportion before. As mentioned before, with the *dYN* step up transformer, the zero sequence source impedance at local terminal of the line is the impedance of the transformer. It's an inductive impedance, the phase angle of which is similar as that of the line impedance. Meanwhile, from the KCL at the fault point $\tilde{I}_{F2}=\tilde{I}_{G2}+\tilde{I}_{H2}$, the amplitude of $\tilde{I}_{H2}$ is much larger than $\tilde{I}_{G2}$ due to the weak-infeed feature of IBR side. Based on the two approximations above,

$$\begin{cases}\arg(\tilde{I}_{H0}/\tilde{I}_{F0})\approx 0^\circ\\ \arg(\tilde{I}_{H2}/\tilde{I}_{F2})\approx 0^\circ\end{cases} \tag{14}$$

For B-C-G faults, the fault resistance is small so that the negative and zero sequence currents have the following relationship,

$$\begin{cases}-\tilde{I}_{H0}=\tilde{V}_{F0}/[Z_{H0}+(1-m)Z_{L0}]\\ -\tilde{I}_{H2}=\tilde{V}_{F2}/[Z_{H2}+(1-m)Z_{L2}]\,.\\ \tilde{V}_{F0}\approx\tilde{V}_{F2}\end{cases} \tag{15}$$

From (14) to (15), since the negative sequence and zero sequence impedances share almost the same phase angle, the phases of the negative and zero sequence fault currents are almost the same, i.e., $\arg(\tilde{I}_{F2})\approx\arg(\tilde{I}_{F0})$. From (13),

$$\arg(\tilde{I}_{F2})\approx\arg(\tilde{I}_{F2}+\tilde{I}_{F0})=-\arg(\tilde{I}_{F1}) \tag{16}$$

Similarly, according to (12), the result of criterion $\delta\approx 180^\circ$ during B-C-G fault. The main difference between PP and PPG faults is the latter type has zero sequence component. The values of δ during A-B-G and C-A-G faults are 60° and -60° respectively.

Note that the criterion δ cannot be used for three phase faults, since the negative sequence components during symmetrical faults are zero. The three phase faults can be identified via the availability of negative sequence/zero sequence components.

C. The Design of Phase Selection Element

A phase selection method based on the compound proportion criterion is proposed for lines with IBRs. Zero and negative sequence voltages can be used to judge asymmetry and grounding of faults. The flow chart of the phase selection element is shown in Fig. 5.

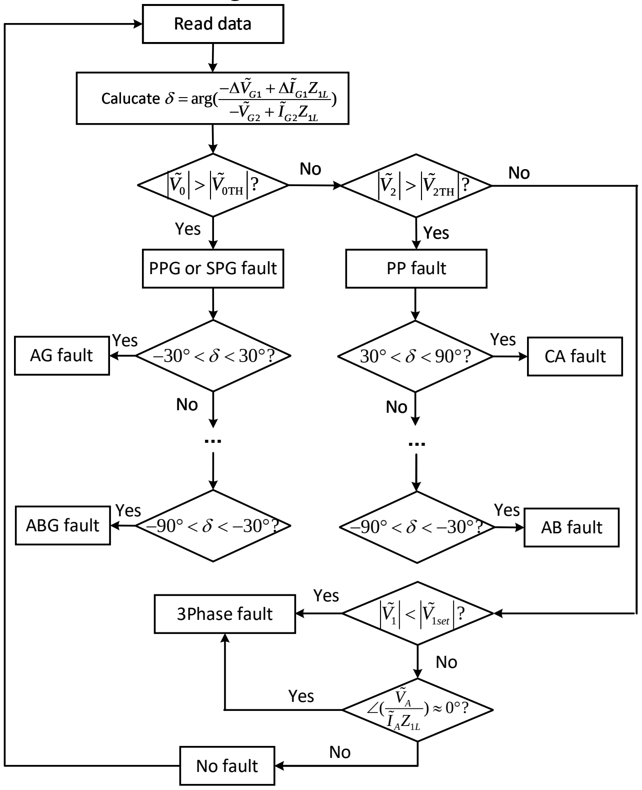

Fig. 5. Flow chart of proposed phase selection method

The work flow of the proposed method can be summarized as follows. Firstly, the zero sequence voltage is used to judge whether it is an asymmetrical grounded fault. Then, judge whether it is PP fault by negative sequence voltage. Once the fault is identified as an asymmetric fault, the fault type can be distinguished by criterion δ . The specific angle range design is shown in the Fig. 6. Each fault type has $\pm 30°$ margin that is enough for proposed compound proportion criterion.

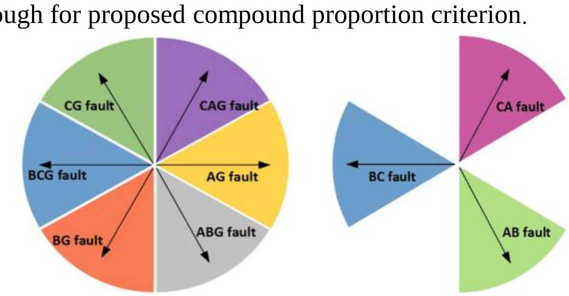

Fig. 6. Angle range of δ, left: PPG or SPG faults, right: PP faults

To sum up, the proposed method does not depend on the specific inverter control strategy, and does not need additional data from the inverter. Compared to the traditional phase selection method, the proposed method considers fault current characteristics when IBR is connected to the local terminal. The proposed method can significantly improve the accuracy of phase selection.

IV. Numerical Experiments and Results

To demonstrate the effectiveness of the proposed method, an example 50Hz, 110KV system with an IBR is built in MATLAB/Simulink. The system is the same as Fig. 2.

Here the proposed method in (11b) is validated. The length of the transmission line is 50 km. The positive (negative) and zero sequence impedances for the entire line are $Z_{L1} = Z_{L2} = 12.47+j37.69\ \Omega$ and $Z_{L0} = 42.50+j94.24\ \Omega$, respectively. The actual source impedance of the remote side is $Z_{H1} = Z_{H2} = 4.82+j18.85\ \Omega$. In this example, Z_{L1}/Z_{H1} is approximately 2. Note that the performances of the proposed method in (11b) could be compromised if the source impedance are comparable or much larger than the line impedance. In this case, if the values of Z_{H1} and Z_{H2} are available, they can be substituted into the expression in (11a) to ensure the best performance of the proposed method.

A. Phase Selection Performances for Various Fault Types

A series of line faults with different fault types occur on the line. The fault resistance is all set as 1 Ω. The control strategy of IBR is the balanced current control [16], which do not inject negative sequence current to grid. The performances of the proposed method, traditional method and existing improved method [10] are shown in the Table II.

Table II. The phase selection results, different fault types

Fault type	Distance *m*	δ	Proposed method	Traditional method	Existing method [10]
AG	10%	-1.3 °	√	×	√
	50%	-1.2 °	√	×	√
	90%	-1.2 °	√	×	√
BCG	10%	174.5 °	√	×	√
	50%	177.5 °	√	×	√
	90%	177.7 °	√	×	√
BC	10%	178.0 °	√	×	√
	50%	178.1 °	√	×	√
	90%	178.3 °	√	×	√
ABCG	10%	—	√	√	√
	50%	—	√	√	√
	90%	—	√	√	√

From Table II, the traditional method cannot provide exact phase selection result from traditional criterion α and β, since the negative sequence current is very small and unstable due to the control strategy of inverters. For the proposed method, the true value of the criterion δ is consistent with the results in Fig. 6. Both the proposed and existing methods can accurately identify fault types during low resistance faults.

B. Phase Selection Performances for Various Fault Resistances

Phase selection of high resistance faults is another important issue for SPG faults, since the fault resistance of SPG fault may exceed 100 Ω and result in small fault current.

A series of asymmetrical ground faults with different fault resistances are tested to verify the performances of proposed method. The maximum fault resistance is considered as 300 Ω for SPG faults and 15 Ω for PPG faults. The performances of the proposed method and the existing improved method [10] is shown in Table III. Note that similar as the results in Section IV.A, the traditional phase selection method still cannot work correctly due to the issues of the negative sequence current, and are therefore not shown in Table III.

Sign 'N.A.' in Table III refers to the result that does not match any fault type for existing improved method [10]. The reason is the phase angle error for the existing improved method exceeds its angle margins. The results prove that the existing methods have poor phase selection results during high resistance faults. Meanwhile, proposed method is almost not affected by the ground resistance. Therefore, the proposed method can correctly identify the fault phase, while the traditional method and the existing improved method fail to select the correct fault phases.

Table III. The phase selection results, different fault resistance

Fault type	Distance *m*	Fault resistance	δ	Proposed method	Existing method [10]
AG	10%	0.1Ω	-1.3°	√	√
		15Ω	-0.9°	√	√
		100Ω	0.5°	√	√
		300Ω	0.6°	√	×(N.A.)
	50%	0.1Ω	-1.2°	√	√
		15Ω	-0.6°	√	√
		100Ω	0.5°	√	×(N.A.)
		300Ω	0.6°	√	×(N.A.)
	90%	0.1Ω	-1.2°	√	√
		15Ω	-0.2°	√	√
		100Ω	0.8°	√	×(N.A.)
		300Ω	0.9°	√	×(N.A.)
BCG	10%	0.1Ω	174.6°	√	√
		15Ω	177.2°	√	×(N.A.)
	50%	0.1Ω	177.6°	√	√
		15Ω	177.5°	√	×(N.A.)
	90%	0.1Ω	178.0°	√	√
		15Ω	176.4°	√	×(N.A.)

C. The Influence of Control Strategies of IBRs

The fault current characteristics is depended on the control strategies of IBRs. The strategy to inject negative sequence current during fault is particularly common in Europe. To verify the adaptability of the proposed method, the control strategy is replaced by PQ control with negative sequence current injection. In this case, another set of experiments is conducted. The results are shown in Table. IV.

Table IV. The phase selection results, updated control strategies

Fault type	*m*	Fault Resist.	δ	Prop. method	Trad. method	Exist. method [10]
AG	10%	1Ω	-2.7°	√	×(ABG)	√
		100Ω	-4.7°	√	×(ABG)	×(N.A.)
	50%	1Ω	-3.5°	√	×(N.A.)	√
		100Ω	-3.6°	√	×(ABG)	×(N.A.)
	90%	1Ω	-3.7°	√	×(N.A.)	√
		100Ω	-0.2°	√	×(ABG)	×(N.A.)
BCG	10%	1Ω	-172.9°	√	×(CG)	√
		15Ω	-157.0°	√	×(CG)	√
	50%	1Ω	-179.1°	√	×(CG)	√
		15Ω	-177.8°	√	×(CG)	×(N.A.)
	90%	1Ω	179.9°	√	×(CG)	√
		15Ω	177.6°	√	×(CG)	×(N/A)
BC	10%	1Ω	177.3°	√	√	×(N.A.)
	50%	1Ω	177.6°	√	√	×(N.A.)
	90%	1Ω	178.0°	√	√	×(N.A.)

For systems with negative sequence current injection during fault, traditional phase selection method cannot distinguish asymmetrical ground fault correctly due to the phase difference between positive and negative sequence output currents. The existing improved method assumes no negative sequence current during the fault, therefore fails to identify fault types in some cases. In comparison, the proposed method still works well with correct phase selection results.

V. CONCLUSION

Due to the unique output characteristics of the IBRs during asymmetrical fault, the traditional phase selection method cannot work and the fault type cannot be correctly identified. This paper proposes an improved phase selection scheme based on compound proportion criterion. First, the limitations of the traditional phase selection method are presented. Next, the criterion is proposed based on fault sequence current components. The method can distinguish fault types based on the compound proportion criterion. Numerical experiments for a line terminated by the IBR prove that the proposed method can accurately identify various fault types with different fault resistances and IBR control schemes, while the traditional method and existing improved methods fail to correctly identify the fault phase in specific scenarios.

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