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Impact of 'intermediate' sources on distance protection of transmission lines

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Abstract: A strategy to evaluate the impact of intermediate sources on the performance of transmission line distance protection is proposed in this study. The influence of an intermediate infeed on the sensitivity of the reach setting and the resulting tripping performance of a distance protection scheme is the main emphasis of this study. The proposed strategy considers the effectiveness of various protection schemes on the protection challenges expected on the National Grid transmission network due to future changes in the generation mix. PowerFactory (DIgSILENT PowerFactory software package) will be used to simulate a double circuit transmission network, when a fault occurs and the strength of the main and intermediate sources change from weak to typical to strong. This study discusses various solutions to the problems observed and a methodology for adapting the grading strategy of distance protection as transmission networks evolve into the future.

1 Introduction

Parallel circuits are widely utilised in high-voltage (HV) transmission networks to improve the reliability and security of the system [1]. Distance relays are commonly used for the protection of transmission lines and they operate by measuring the impedance to a fault on the protected line or adjacent lines. If the measured impedance is below the actual impedance of the protected zone, a relay initiates, after an appropriate delay, the tripping of the circuit breakers required to clear the fault [2, 3]. A system with a high fault level contributes sufficient fault current for the relay to operate correctly. However, as the fault level reduces, insufficient fault current may not allow the relay to operate or may result in a delayed operating time [4–6].

Greater utilisation of distributed converter-based generators, flexible alternating current transmission system (FACT) devices, HVDC links and a decline in the existing bulk synchronous power generators has implications for the effectiveness of existing protection schemes. According to the '2014 UK National Grid's Electricity Ten year statement' document, the 'Gone Green' GB electricity transmission strategy shows an increase in embed degenerations from 14% in 2014, 29% in 2020 and rising to 43% in 2035 [7, 8]. The document also highlighted the reduction of coal capacity from 18 GW in 2014 to 7 GW by 2020 and to 0 GW by 2030. In contrast, the system operating framework (SOF) 2016, UK electricity transmission indicates that the largest regional decline of minimum short-circuit level occurs on the northwest and West midlands will be 82% by 2025/26 [9]. Reference [9] discusses system strength will be low when a transmission demand is low because fewer large synchronous generations will be in-service and this requires a review of backup protection. In addition, areas such as southeast England is heavily dependent on limited double transmission line corridor, one large synchronous generator and with a greater availability of non-synchronous generations. In such areas, assessing the effectiveness of distance protection is needed.

Several studies have been conducted on the future protection challenges associated with converter-dominated power systems. However, there is limited published data on the challenges of conventional protection schemes when operating with low system inertia and a low fault level [10–12].

The proposed paper will assume a section of a power system consisting of a double circuit feeder with one source at the sending end. If one of the circuits on the first feeder section is out-of-service, then if a fault is located on one of the adjacent feeders, the measured fault impedance may be small. Alternatively, when both circuits are in-service, but only one adjacent feeder is in-service, the measured fault impedance would be greater than the actual reach setting. In addition, when a double circuit feeder with a source at both ends is operated, the measured impedance would be different from the above cases and depends on the fault level. Consequently, it is necessary to investigate the variance in the measured impedance errors, and especially those associated with the zones 2 and 3 elements. The process involves a setting calculation procedure that considers worst-case scenarios.

If one considers the connection of an intermediate generator into the double circuit transmission feeder, the fault impedance measured by the relay may change significantly, depending on the strength of the intermediate infeed. This is because the current contribution from the infeed causes a voltage drops in the loop circuit leading to an increase in the voltage at the relay location. Normally, the measured impedance errors for the zone 2 and zone 3 elements become large and this may lead to under reach problems, especially if these errors are not resolved by altering the reach setting of the zones. Hence, the operating reach of a distance relay may be inadequate and indeterminate, especially if the current contribution from the infeed is significant. Consequently, it is important to investigate the effect of various types of intermediate sources on the sensitivity of the measured reach impedances.

The purpose of this paper is to examine the impact of adding intermediate sources on the reach setting and operating times of distance protection. PowerFactory (DigSILENT software package) will be used to simulate a fault on a double circuit transmission network when the main and intermediate sources change from weak to typical to strong [13]. The influence of the intermediate infeed on the reach setting and the tripping performance of a distance protection scheme is the main emphasis of this paper. Various solutions to the problems observed will be discussed and a methodology for adapting the grading strategy of distance protection will be proposed.

2 Proposed method

To investigate the reach impedance of distance relay, and especially the impact of adding intermediate sources, DigSILENT power factory was used to simulate a network model with various fault levels of mixed generation. The modelled network is then exported

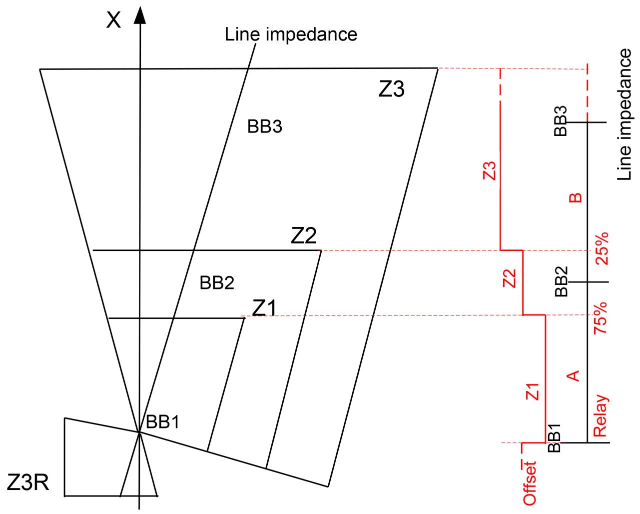

Fig. 1 *Quadrilateral characteristics of the distance relay*

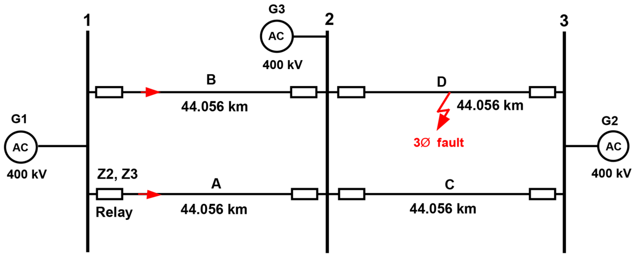

Fig. 2 *Effect of parallel line on backup protection on one of the adjacent double circuit lines during external fault*

to omicron test universe software package and the effectiveness of a distance relay was examined and compared with the simulated test results.

2.1 Distance relays

Distance relay measures the impedance of the line and operates if the measured impedance is less than the actual impedance of the line. It is a multi-zone time-stepped delayed backup protection. Most distance relays operate with direct transfer tripping and provide either an instantaneous or delayed fault clearance when a failure of main protection occurs. Factors that influence the operating performance of the relay includes fault location, line length and source to line impedance ratio. For example, as the system fault current drops, faults tend to become resistive and a distance relay may operate in delayed time or may even fail to see the fault. Hence, a quadrilateral distance characteristic is preferable during a low fault current and in addition may clear faults behind the relay, see a resistive fault and deal with problems of load encroachment (Fig. 1).

In accordance with the National Grid protection policy, the zone 1 forward looking elements are set at 75% of the protected line and operate instantaneously. Zone 2 forward looking is set to 125% of the protected line and operates with a delay of 0.5 s. Zone 3 forward looking is set to 100% of the protected line plus 125% of the longest adjacent line and 10% of the protected line for reverse looking, both have a backup delay of 1 s [14].

2.2 Transmission model network

Fig. 2 describes a double circuit transmission model, in which a relay is located on circuit A and supplied from a current transformer with a ratio of 2000:1 A and a voltage transformer with a ratio of 400 kV:110 V. The length of each line is 44.056 km. The positive and negative sequence impedance values are:

$Z1 = Z2 = 0.0142 + \text{j}0.2748\ \Omega/\text{km}$.
$Z0 = 0.0776 + \text{j}0.7829\ \Omega/\text{km}$.

Table 1 Distance relay zone setting [14]

Zone setting	Role of protection	Direction of measurement	Zone timer, s
zone 1	main protection	forward looking	0
zone 2	backup protection	forward looking	0.5
zone 3	backup protection	forward reverse+	1

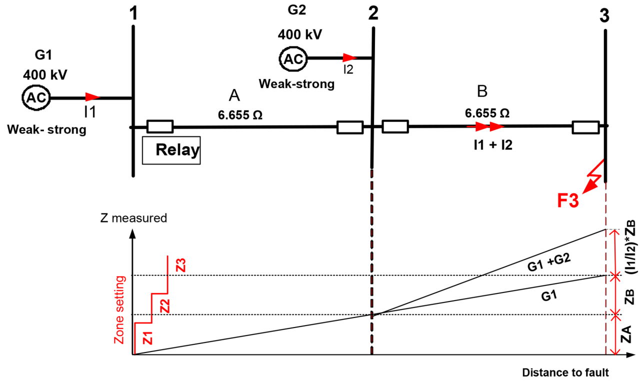

Fig. 3 *Effect of intermediate sources on reach setting*

Consider source G1 ON, G2 and G3 OFF, and assume a three-phase fault is located on 50% of feeder D. The delayed zone 2 and zone 3 elements at relay A can clear the fault. For adaptive relay setting calculations, the following implications can be considered. Assume that:

i. Feeders B and C are disconnected; the reach setting calculation can be referred to Table 1.
ii. Feeder B is disconnected, the current flow in feeder D will be halved and half the impedance value is taken into consideration. In addition, the measured impedance seen on the remote end of busbar 3 is equal to the reach setting of zone 2. The zone 3 reach setting overreaches the measured impedance by 20% and can see faults beyond busbar 3 and this should be resolved by lowering the reach setting.
iii. Feeder C is disconnected, the current contribution on feeder D will be doubled and the relay will only cover 50% of the adjacent line. The zone 2 and zone 3 under reaches by 16.67 and 30%, respectively. Thus, the effective reach setting of the zones 2 and 3 on the adjacent line is only 25 and 62.5%. The relay may fail to detect a fault on the remote end of feeder D. Possible solution is to lower the zone 2 setting to $1.25 \times Z_{12}$, and increase the Z3 backup setting to $1.5 \times [Z_{12} + 2 \times Z_{23}]$.
iv. All sources G1, G2 and G3 are in-service, the strong infeed from G2 amplify the impedance where the variation of measured impedance is non-linear which consists of a parabolic course. These causes under reach problem, and due to 'blind zones' faults on the next line are left uncleared by backup distance protection. If a feeder consists of infeed from both ends or on meshed networks; it is preferable to apply graded directional fault clearance. In the next section, the effect of infeed sources on the sensitivity of distance protection will be discussed in detail.

2.3 Effect of intermediate infeed on distance relay setting

In this section, a radial system with intermediate infeed source, located between the relay and fault points is first assessed as shown in Fig. 3.

In Fig. 3, the measured impedance at the relay location is calculated as

$$Z_{\text{relay}} = Z_{\text{A}} + Z_{\text{B}} + \frac{I2}{I1} Z_{\text{B}} \qquad (1)$$

$(I2/I1)Z_{\text{B}}$ is the measured error caused by the infeed source.

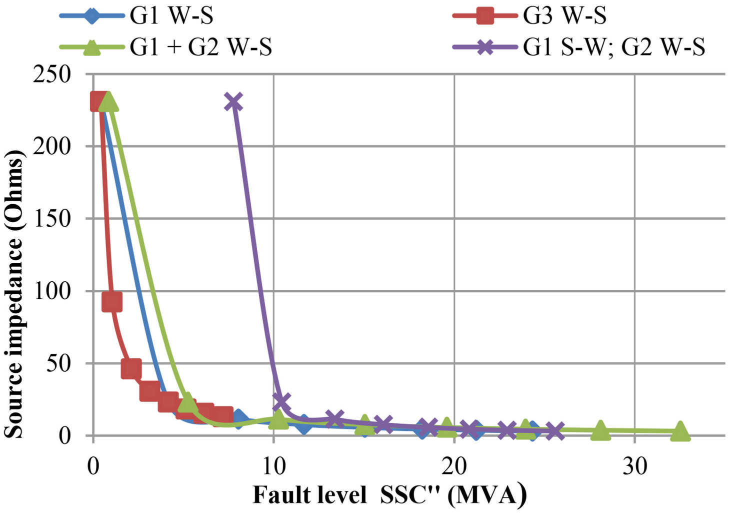

Fig. 4 *Current infeed at fault location, short circuit current (SCC)'' (MVA)*

Table 2 Effect of intermediate infeed on relay setting

Generation mix		Percentage increase of Z_{measured} versus Z_{setting}		
G1	G2 (infeed)	Z2	Z3	Error
weak	weak	33.63	167.58	**high**
strong	weak	0.768	68.97	**low**
weak	strong	596.9	1857.6	**high**
strong	strong	12.64	104.59	**low**

Bold values indicates the measured impedance error is highest when the infeed (intermediate) source, G2 is strong while G1 (i.e. where relay located) is weak.

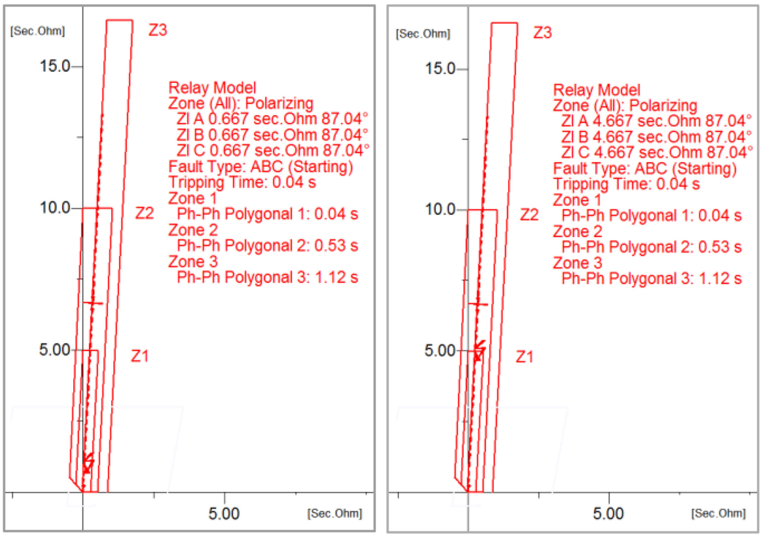

Fig. 5 *Tripping of F21 distance polygonal (3Φ fault)*

In zone 2, the infeed source increases the measured impedance and in the downstream it influences the over-reaching zones, backup zones and fault clearing stages. Whilst a fault is located at the remote end of busbar 3, a calculated short-circuit current contribution from individual and mixed generation is presented in Fig. 4.

In Fig. 4, *G* is the generator/source, *W* is the weak source and *S* is the strong source and the three-phase initial peak currents of G1 and G2 are 71.12 and 13.01 kA, respectively. Considering the generation mix, i.e. when both sources are operated from weak to strong; a maximum fault current is seen at the fault location.

Table 2 presents the percentage increase of measured impedance and impedance reach setting of the relay. The highest increase in measured impedance is seen when G1 is weak and G2 is strong, whereas the minimum percentage increase is obtained when G1 is strong and G2 is weak. With the presence of intermediate sources, altering the zone reach setting is possible, when the source behind the relay contributes sufficient fault current. However, when the infeed source is strong and if the main source is weak, the zones 2 and 3 operating reach setting will be indeterminate. Alternatively, installing a relay at busbar 2 can successfully detect faults on feeder B or beyond.

3 Results and discussion

3.1 Relay characteristics test

In this section, the tripping performances of the F21 distance polygonal relay (*R*1) is first assessed.

Fig. 5 shows a simulated tripping characteristics of the distance relay when a 3Φ fault is located on 10 and 75% of the line length. It tripped in zone 1 time (40 ms) and satisfies the relay setting configuration and tripping times are justified.

Table 3 presents tripping times of time-stepped zones of distance relay. The relay model (*R*1) simulated on power factory is compared with the actual relay tested using omicron test universe

Table 3 Tipping performance of model versus actual relay

Zone setting	Faults on percentage of line, %	Relay trip time, *t*, ms			
		*R*1	*R*2 tested		
		1, 2, 3Φ	1Φ	2Φ	3Φ
*Z*1	10	40	20.6	20.30	20.2
	70	40	18.9	34.3	42
*Z*2	100	530	518	517	518
	125	530	518	519	520
*Z*3	200	1120	1070	1090	1030
	240	1120	1028	1.043	1045
offset	−10	1120	1019	1021	1026

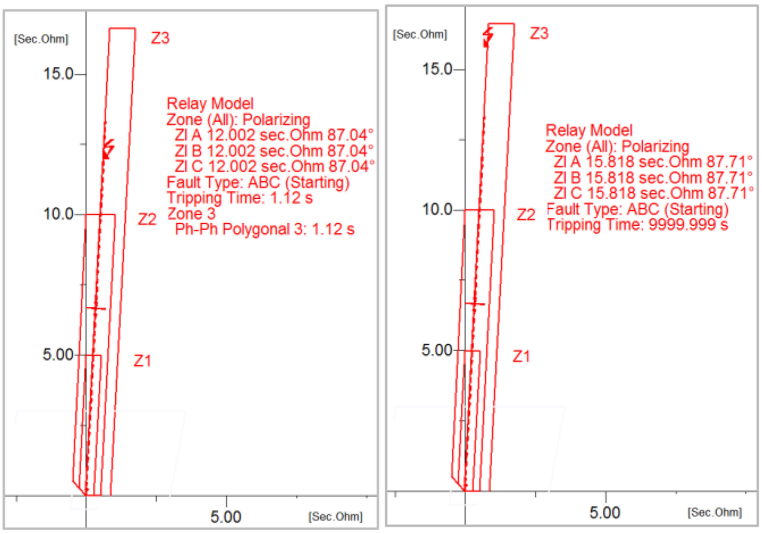

Fig. 6 *Relay without and with intermediate sources*

(*R*2). Multiple faults located on 10, 70, 125 and 240% of the line length are tested. For faults close to the relay, the relay operates fast compared with the faults on the end of all three zones which resulted in delayed time. For example, for Φ–Φ faults located on 10% of the line length, the relay tripped after 20.30 and 34.30 ms when the fault is on 70% of the line length. Overall, both relays are effectively operated within the tolerances error margin (i.e. ±20 ms).

3.2 Impact of the intermediate source on distance protection

In this section, the effect of intermediate source on reach impedance is examined.

Fig. 6 shows a relay successfully tripped on zone 3 times (i.e. 1.12 s) when 3Φ fault is located on 80% of feeder B. However, when an intermediate infeed source is added at busbar 2, it failed to clear the fault due to under reach problems discussed in Table 2.

3.3 Generic methods to assess the impact of varied intermediate sources on distance protection

As discussed in Section 2.3, even though the size of the main sources G1, located near the relay is four times bigger than the intermediate sources G2; the measured impedance error encountered by the infeed was significant which prevents the relay to clear faults on adjacent lines. The worst-case scenario is obtained when G1 is weak and G2 is strong.

The generic method to perform short-circuit and distance coordination study under varied intermediate source is presented in Fig. 7. The proposed flowchart describes the way intermediate infeed source increases from weak to strong until the effectiveness of relay failed to detect faults on backup zones 2 and 3 elements (i.e. adjacent lines). In such cases, a relay can be ignored and worth to install a new relay near the intermediate infeed source which can provide a fast fault clearing times on the feeder B.

4 Implication for the impact of the weak and strong sources on distance protection

Fig. 8 shows a transmission system that consists of weak and strong sources. Assume a relay is located near a weak source, and if a fault occurs close to the relay, the short-circuit current contribution from the weak sources may not be sufficient for the relay to trip in zone 1 time. However, a relay located near strong infeed source can clear the fault at zone 2 delayed and this delayed tripping might cause reliability issues. In such applications, a smart relay algorithm with control based on phase–phase under voltage levels and a residual overvoltage level detector or a negative phase sequence current method is essential during weak infeed conditions.

5 Conclusion

The operating behaviours of distance protection, zone coordination and impedance reach setting calculation during the presence and line outage of a double transmission line were discussed in this paper. When feeder B is disconnected, the zone 3 reach setting overreaches the measured impedance by 20% and can see faults beyond busbar 3. In comparison, when feeder C is disconnected, the zone 2 and zone 3 under reaches by 16.67 and 30%, respectively. These changes were resolved by lowering the reach setting of the relay.

The impact of intermediate infeed sources on impedance reach setting, when a fault occurs on the adjacent lines, was studied in this paper. A summary of the impact can be expressed, with reference to Fig. 3 and Table 2, as though the altering zone setting is possible when the intermediate sources are weak, the measured impedance error is significant when it changes from weak to strong; consequently, the reach setting of the relay cannot detect faults on adjacent lines. Fig. 5 validates the simulated tripping characteristics of the distance relay when a 3Φ fault is located on

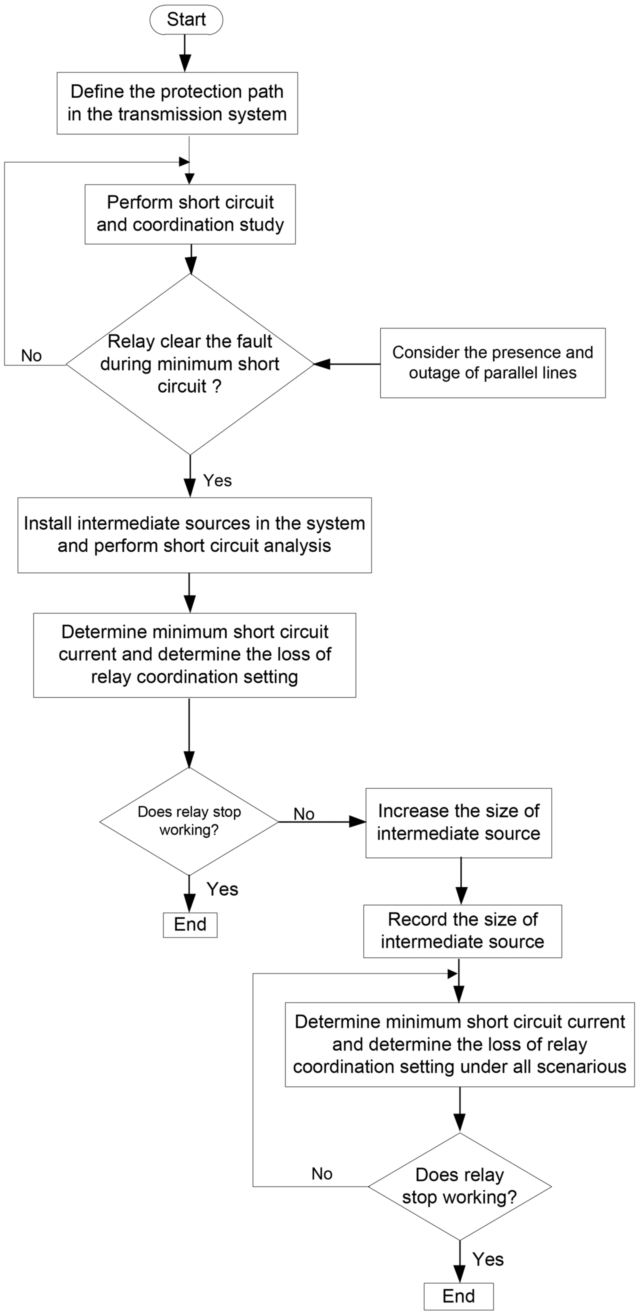

Fig. 7 *Generic method of distance relay coordination study under varied intermediate sources*

10 and 75% of the line length was successful and satisfies the relay setting configuration and tripping times are justified.

Table 3 compares the tripping times of time-stepped zones of distance relay between the relay model and the actual relay tested via omicron test universe. Multiple faults, located on 10, 70, 125 and 240% of the line lengths, were tested. Both relays were effectively operated within the tolerances error margin (i.e. ±20 ms).

The impact of intermediate sources on tripping performance of the relay was examined as shown in Fig. 6. In addition, the generic method to perform short-circuit and distance coordination study under varied intermediate source is presented in Fig. 7. The proposed flowchart describes the way intermediate infeed source increases from weak to strong until the effectiveness of relay failed to detect faults on backup zones 2 and 3 elements. If the relay failed to clear faults on adjacent lines, a new relay installed near the intermediate sources is preferred.

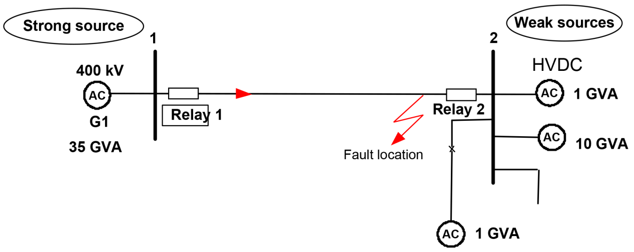

Fig. 8 *Impact of weak and strong sources on distance protection*

The impact of weak and strong infeed sources on the operating performance of relay is discussed in this paper. A smart relay algorithm with control based on phase–phase under voltage levels and a residual overvoltage level detector or a negative phase sequence current method is essential during weak infeed conditions.

6 Acknowledgments

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