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# A Strategy for Refining Fault Zone Identification of Distance Relays

# طريقة لتحسين دقة تحديد منطقة العطل للمتممات المسافية

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## ملخص

يقترح البحث منظومة تعديلية لتحسين دقة تحديد منطقة العطل فى شبكة النقل المحمية بمتممات مسافية لتجنب التشغيل الغير صحيح للمتممات و رفع معدل الاعتمادية، وتتكون المنظومة المقترحة من أربعة مراحل يتم فى الأولى تحديد الخط المعطوب من الشبكة و موقع العطل عليه باستخدام التقديرات الأولية لمناطق العطل التى توصلت اليها المتممات بالحسابات التقليدية ثم يتم فى الثانية حصر المتممات المسافية المشكوك فى تقديرها لمنطقة العطل آليا بناءا على ظروف تشغيل الشبكة، ويتم فى المرحلة الثالثة تقدير منطقة العطل المعدلة للمتممات المشكوك فيها بناءا على تقديرات المتممات المحيطة فى نفس المحطة الفرعية وتطبيق مجموعة من القواعد، ويتم فى المرحلة الرابعة حساب منطقة العطل النهائية و الصحيحة للمتممات المشكوك فيها بمقارنة منطقة العطل المعدلة لمتممى النهاية على نفس الخط و تطبيق مجموعة أخرى من القواعد، و قد ظهر فاعلية المنظومة المقترحة عند تطبيقها على شبكة نقل منطقة وسط الدلتا فى مصر عند ظروف أعطال متنوعة حيث تم تصحيح العديد من تقديرات المتممات المسافية و تفادى التشغيل الخاطئ.

## Abstract

A modified setting strategy for deciding the correct fault zone in distance relays is introduced. It depends on exchanging information between local relays in the same station in addition to a command from the remote end relay. As a start point, the conventional setting strategy is applied to initially determine which distance relays should operate and their zones of operation. Based on this preliminary information, the proposed system locates the faulty line. Then, the set of relays with suspected preliminary operation zones, that needs to be examined, is identified using some rules. This limited set of relays is solely considered in the next validation stages to save the processing time. The scheme verifies the relay zone reach in two steps. In the first step, a rule-base is applied to determine a modified zone for the relay. In the second step, another rule-base is applied to determine the final zone for the relay based on its modified zone. The governing rules for the proposed strategy are presented. The strategy is examined against a wide range of setting problems of a real part of a high-voltage network. The results confirm that the proposed strategy achieves the required accurate, sensitive, and selective relay operation.

## 1. Introduction

Distance relays have an assigned area known as the primary protection zone, but they may properly operate in response to conditions outside this zone. In these instances, they provide backup protection for the area outside their primary zone. This is designated as the backup or overreached zone [1]- [5]. Selectivity (also known as relay coordination) is the process of applying and setting the protective relays that overreach other relays such that they operate as fast as possible within their primary zone, but have delayed operation in their backup zone. This is necessary to permit the primary relays assigned to this backup or overreached area time to operate. Otherwise, both sets of relays may operate for faults in this overreached area, the assigned primary relays for the area and the backup relays. Operation of the backup protection is incorrect and undesirable unless the primary protection of that area fails to clear the fault [6]-[10].

In power networks, distance protection is usually used as "main-1" and "main-2" for long transmission lines. It is also used as "main-2" for short transmission lines as well as for

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underground cables which are typically protected with line differential protection as "main-1". With the traditional setting strategies, the distance relay (as main-1) may fail to respond correctly to some faults. Also, line differential protection can suffer maloperation for one reason or another. Then, the distance relay (as main-2) is required to respond selectively and reliably [3], [10].
The different factors affecting the distance relay reach calculation are 1) sensed fault current, 2) fault resistance, 3) load encroachment, 4) an existing long line after a short line or vice-versa. The actual reach of the relay can be severely affected and sensitivity will be missed. In the best case, the relay operates with unaccepted delay time [1], [4].
The Available solutions in the literature include trials to minimize the errors in estimating the impedances, for example, by suggesting an online measurement of transmission-line impedance. Data communication is an essential part for implementing this proposal [5]. An adaptive distance protection scheme for parallel circuits, in which a correction factor based on the information of the surrounding system of the protected line under different operating status was used in the impedance calculation [6]. Another adaptive technique adjusts its zone reach based on the availability of input signals from surrounding system to achieve optimal distance protection performance [1], [3]. Others try to increase the second-zone coverage of distance relays without causing overreach problems [7], [8].

The system proposed in this work locates the line that contains the fault using the preliminary information about which distance relays have operated and their zones of operation applying the conventional setting strategy. Then, the set of relays with suspected preliminary operation zones, that needs to be examined, is identified using some rules. This limited set of relays is solely considered in the next validation stages to save the processing time. The scheme verifies the relay zone reach in two steps based on the availability of input signals from local relays in the same substation in addition to a command from the distance relay on the other end of the protected line that is transmitted using any existing teleprotection system [10], [11]. In the first step, a rule-base is applied to determine a modified zone for the relay. In the second step, another rule-base is applied to determine the final zone for the relay based on its modified zone. The data needed from the remote end are obtained in the form of the traditional transfer trip signal in the pilot trip schemes with minor modifications. Hence, there is no delay time added in the proposed scheme compared to the techniques that depend on data from the remote end. This strategy will alleviate problems inherent in present strategies using minor modifications to the frequency-modulation (FM) circuit of the pilot scheme [11] - [13]. The proposed modified setting strategy (MSS) is applied to different case studies in a real high-voltage network. These case studies show how the MSS avoids practical problems that severely affect the conventional setting strategies.

# 2. Proposed setting strategy

The "setting strategy" is the way in which relays are set to achieve the goals of selectivity and security of the power transmission system. A relay setting strategy is translated into a number of rules for the relaying system. In the proposed strategy, there are three stages within the protective algorithm.

### 2.1 Architecture

1) In the first stage, the distance relay (DR) at each end of a transmission line calculates a self pre-estimated fault zone and direction (forward F / reverse R) based on its own measured voltage and current according to conventional DR setting rules [10]. The impedances calculated at this stage are affected by the problems mentioned in the introduction and, hence, are not expected to be completely accurate. Then, the faulted line(s) is identified as the line which its two terminal relays "see"

the fault in the forward direction. There is no need to examine the pre-estimated fault zone of all the relays in the system to accelerate the protective algorithm. Accordingly, a set of mostly concerned relays with possible incorrect pre-estimated fault zone, will be called hereafter suspected relays, is determined as follows.

a) the relays on the faulted line joining buses i and j.

b)first layer: the relays on the lines which are directly connected to the faulted line ij, i.e. connecting bus i to set of buses K or connecting bus j to set of buses M.

c)second layer: the relays on any next line(s) to lines in part (b) above, connecting any bus in the set K to another bus in a set of buses N or connecting any bus in the set M to another bus in a set of buses O, if its length is greater than 125% of any previous line in the first layer.

2) In the second stage, based on this local information, each relay updates its self pre-estimated fault zone and calculates a modified fault zone according to specific rules. The value of the modified-fault zone is used only within the corrective algorithm and no trip/block action is based on it.

3) In the third stage, each relay sends a command to the corresponding relay at the other end of the TL using a specific modulated frequency via any available communication media. This command is interpreted by the demodulating circuit of the remote end to infer the value of the modified fault zone at the other end. Sending a command to the other end is common in all conventional protective pilot schemes. However, in the proposed strategy, the value of the modulated frequency is used to transfer the value of the modified fault zone calculated at the other end. The final decision at each relay is based on comparing the two modified fault zones calculated at both ends according to some rules as given below.

**2.2 Rules for estimating the modified fault zone**

The modified fault zone is estimated for each relay in the suspected relays set based on comparing the available data from local surrounding relays according to the following rules [1], [7].

1. The modified fault zone of a relay is taken as the zone with the smallest zone number among the considered local relays set.

2. The fault direction of the modified fault zone of a relay is similar to the fault direction of its pre-estimated zone.

3. If a local relay does not "see" the fault at all but receives the fault zone's reach from other local relays, then the relay takes the modified fault zone as the smallest zone number of all received local values in a reverse direction.

4. If the fault direction of all local relays is reverse, then the fault is located at the busbar itself. In such a case, the modified fault zone for all relays is identified as zone-1 with a reverse direction.

**2.3 Rules for estimating the final fault zone**

The modified fault zones at both end relays of a line are compared together in the third stage according to the following rules to produce their final fault zones [1], [4].

1) If the two fault directions are forward at both ends, then the final zone reach is identified as zone-1 at both ends irrespective of the values of the modified fault zones at the two ends. For example, comparing (Z1, Forward) with (Z2, Forward), will result in a final fault-zone identification as (Z1, Forward) at both ends.

2) If the two fault directions are opposite, then the final zone reach at each side is "the smaller zone-number plus one." For example, comparing (Z1, Forward) calculated at side-1 with (Z2, Reverse) calculated at side-2, will result in a final fault-zone identification as (Z2, Forward) at side-1 and (Z2, Reverse) at side-2. The fault direction at each end is always unchanged.

3) To be consistent with the known setting rules, any zone reach in the final stage in a reverse direction will be reset to Z4, i.e. the trip time for any reverse fault will be equal to the zone-4 trip time. For example, (Z2, Reverse) will be reset to (Z4, Reverse).

Zone-1 in the MSS covers the total length of the protected line while zone-2 covers the full length of any line following the protected line irrespective of its length. Similarly, zone-3 covers the full length of any line following the second zone. Fig.1 reveals a flowchart of the proposed setting strategy.

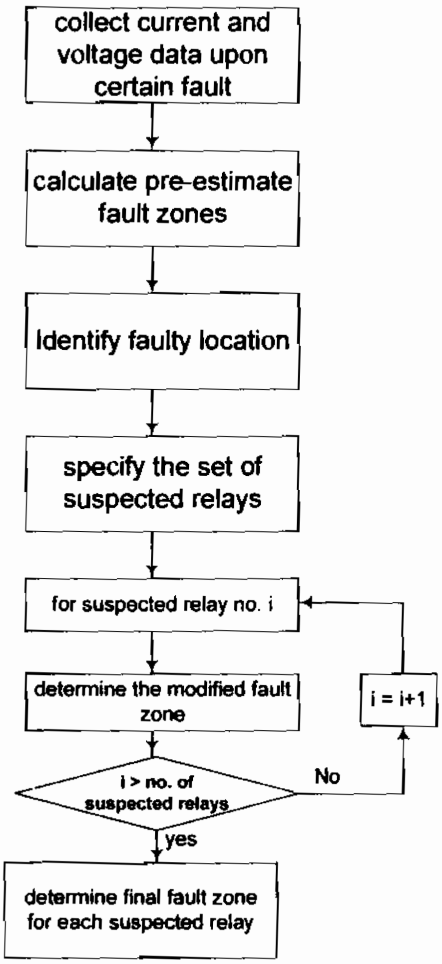


Fig.1 Flowchart of the modified setting strategy

# 3. Results and Discussion

To study the performance of the MSS, a real part of the 220 kV Delta transmission network, delta zone, Egypt is considered. It is composed of 15 busbars, 4 generators and 18 lines. Two additional lines 19, 20 are assumed parallel to line 12. The one line diagram of the studied network is depicted in Fig.2. The system data is given in [14]. Line data is listed in Table 1. Each line is equipped with two distance relays at its two ends. Each relay is looking toward the opposite end of the line. The network is modeled and simulated using PSCAD software to determine the line currents and bus voltages for the fault cases examined below.

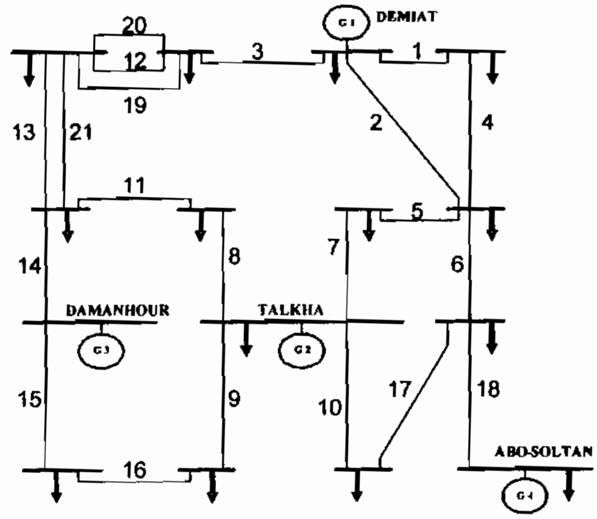


Fig.2One-line diagram of the studied transmission network

Table 1 Line data

| LINE NO. | R (Ω/km) | X (Ω/km) | B (moh/km) | Lehgth (km) |
|---|---|---|---|---|
| 1 | 0.0412 | 0.302 | 3.72 | 10 |
| 2 | 0.0412 | 0.302 | 3.72 | 30 |
| 3 | 0.0412 | 0.302 | 3.72 | 76.2 |
| 4 | 0.0412 | 0.302 | 3.72 | 33 |
| 5 | 0.0412 | 0.302 | 3.72 | 56.8 |
| 6 | 0.0412 | 0.302 | 3.72 | 100 |
| 7 | 0.0412 | 0.302 | 3.72 | 18 |
| 8 | 0.0412 | 0.302 | 3.72 | 60 |
| 9 | 0.0412 | 0.302 | 3.72 | 95 |
| 10 | 0.0412 | 0.302 | 3.72 | 65 |
| 11 | 0.0412 | 0.302 | 3.72 | 55 |
| 12 | 0.0412 | 0.302 | 3.72 | 30 |
| 13 | 0.0412 | 0.302 | 3.72 | 30 |
| 14 | 0.0412 | 0.302 | 3.72 | 23 |
| 15 | 0.0412 | 0.302 | 3.72 | 42 |
| 16 | 0.0412 | 0.302 | 3.72 | 46.2 |
| 17 | 0.0412 | 0.302 | 3.72 | 75 |
| 18 | 0.0412 | 0.302 | 3.72 | 37.5 |

In the system shown in Fig.2, there are three parallel lines (L12, L19, and L20). There is also short line(s) connected next to long line(s). These conditions can cause DR initial maloperation that needs correction by the MSS as will be remarked in the following case studies. In Tables 2- 18 below, D refers to direction and Z refers to zone.

## 3.1 System performance

### 3.1.1 Three phase to ground fault in the middle of line 12

From the three-phase currents and voltages at each relay obtained by PSCAD simulation of the system, the fault zone reach of each relay is estimated according to the traditional setting rules [2], [10]. These are provided in Table 2.

Table 2 Pre-estimated fault zone for all relays for 3phase fault in line 12

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z2 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z4 | R | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | R | R11-1 | Z4 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | F | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z1 | F | R19-1 | Z4 | R |
| R5-2 | Z4 | R | R12-2 | Z1 | F | R19-2 | Z4 | F |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | R |
| R6-2 | Z4 | F | R13-2 | Z3 | F | R20-2 | Z4 | F |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z4 | R |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z3 | F |

It is observed that the two relays at the end of the line 12 see the fault in zone 1 at forward direction. So, the fault is at the middle 60% of line 12 (30 km). A more accurate fault location can be found from the average measured relay-to-fault impedance at both end relays. The measured fault reactance of the right-hand relay is 4.45. So, the fault is at 4.45/0.302= 14. 73 km from the line 12 right end. The measured fault reactance of the left-hand relay is 4.49. So, the fault is at 4.49/0.302= 14.87 km from the line 12 left end. Then, the falt location is at: (14. 73+ (30-14.87))/2=14.93 km from the line 12 right end which is accurate enough compared to the actual 15 km fault location. The suspected relays are (R3-1,R3-2,R12-1,R12-2,R13-1,R13-2,R19-1,R19-2,R20-1,R20-2,R21-1 and R21-2). The modified and final fault zone for each of the suspected relays is to be identified. Selecting two facing relays R19-1, R19-2 and applying the MSS rules, Table 3 can be formed.

Table3 Pre-estimated, modified and final fault zones for R19-1, R19-2

| | At relay19-1 | | | At relay 19-2 | | |
|---|---|---|---|---|---|---|
| | ID | Z | D | ID | Z | D |
| Group-1:<br>Self pre-estimation | R19-1 | Z4 | R | R19-2 | Z4 | F |
| Group-2:<br>Collected local information | R12-1<br>R20-1 | Z1<br>Z4 | F<br>R | R13-1<br>R12-2<br>R20-2<br>R21-1 | Z4<br>Z1<br>Z4<br>Z4 | R<br>F<br>F<br>R |
| Group-3:<br>Modified fault zone | R19-1 | Z1 | R | R19-2 | Z1 | F |
| Group-4:<br>Final fault zone | R19-1 | Z2<br>Z2→Z4 | R | R19-2 | Z2 | F |

The modified fault zone is determined as the smallest zone number of all local relays according to rule 1. The direction of modified fault zone at each side is identical to that of the transmitter relays (R19-1 and R19-2) according to rule 2. The final fault zone's category is obtained by comparing these two modified fault zones according to the rules. R19-2 which originally locates the fault as (Z4, Forward) will now locate it correctly as (Z2, forward) as shown in Table 3. R19-1 will continuously see the fault in reverse direction (Z2, Reverse). To be consistent with the known setting rules, (Z2, Reverse) at relay R19-1 will be reset to (Z4, Reverse) according to rule 3. Similar analysis can be repeated for the other suspected relays. As another example, Table4 shows Pre-estimated, modified and final fault zone for R13-1, R13-2.

The pre-estimation shows that R13-2 incorrectly locates the fault in zone-3, not in zone-2 as it should be. The modified fault zone is determined as the smaller zone number of local relays, according to rule1.The direction of the modified fault zone at each side is identical to that of the transmitter relays (R13-1 and R13-2) according to rule 2.

Table4 Pre-estimated, modified and final fault zone for R13-1, R13-2

| | At relay13-2 | | | At relay 13-1 | | |
|---|---|---|---|---|---|---|
| | ID | Z | D | ID | Z | D |
| Group-1: Self pre-estimation | R13-2 | Z3 | F | R13-1 | Z4 | R |
| Group-2: Collected local information | R21-2 | Z3 | F | R19-2<br>R12-2<br>R20-2<br>R21-1 | Z4<br>Z1<br>Z4<br>Z4 | F<br>F<br>F<br>R |
| Group-3: Modified fault zone | R13-2 | Z3 | F | R13-1 | Z1 | R |
| Group-4: Final fault zone | R13-2 | Z2 | F | R13-1 | Z2<br>Z2→Z4 | R |

In the second stage of P-SS, the modified fault-zone and fault direction of R13-1 and R13-2 are compared according to rule 2. The final fault-zone is determined as zone-2, which is "one digit higher than the smaller zone-number of the two modified fault zones". With MSS, the fault detected by relays R13-2 (or R21-2) will be correctly cleared with zone-2 clearing time and not zone-3. This improves the overall stability of the network. It is noted also that with MSS, the second zone covers the total length of any next line to the relay line, e.g., zone-2 for R13-2 covers the full length of lines 12, 19, 20. The voltage and current measuring errors as well as other factors, which limit the distance relay reach in conventional strategies, are avoided.

3.1.2 Three phase to ground fault in the middle of line 21

The fault zone reach of each relay is estimated according to the traditional setting rules [2], [10]. These are provided in Table 5. From Table 6, the fault is at the middle 60% of line 21 because the two relays at the end of the line 21 see the fault in zone 1 in forward direction. The suspected relays are R11-1,R11-2,R12-1,R12-2,R13-1,R13-2,R14-1,R14-2,R19-1,R19-2,R20-1,R20-2,R21-1 and R21-2.

Table5 Pre-estimated fault zone for all relays for 3phase fault in line 21

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z4 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z4 | R | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | F | R11-1 | Z1 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | R | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z4 | R | R19-1 | Z4 | R |
| R5-2 | Z4 | R | R12-2 | Z4 | F | R19-2 | Z4 | F |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | R |
| R6-2 | Z4 | F | R13-2 | Z4 | F | R20-2 | Z4 | F |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z1 | F |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z1 | F |

Selecting a local relay R13-1, R13-2 and applying the MSS rules, the modified and final fault zone for the suspected R13-1, R13-2 are obtained as in Table 6. By applying the rules of MSS, relay R13-2 which originally locates the fault as (Z4, Forward) will eventually locate it correctly as (Z2, forward) as shown in Table 6. The other relay, R13-1 will continuously see the fault in reverse direction (Z2, Reverse). To be consistent with the known setting rules, (Z2, Reverse) at relay R13-1 will be reset to (Z4, Reverse) according to rule 3.

Table6 Pre-estimated, modified and final fault zone for R13-1, R13-2 for 3-phase fault in line 21

| | At relay13-1 | | | At relay 13-2 | | |
|---|---|---|---|---|---|---|
| | ID | Z | D | ID | Z | D |
| Group-1: Self pre-estimation | R13-1 | Z4 | R | R13-2 | Z4 | F |
| Group-2: Collected local information | R21-1<br>R20-1 | Z1<br>Z4 | F<br>R | R21-2<br>R11-2<br>R14-1 | Z1<br>Z4<br>Z4 | F<br>R<br>R |
| Group-3: Modified fault zone | R13-1 | Z1 | R | R13-2 | Z1 | F |
| Group-4: Final fault zone | R13-1 | Z2<br>Z2→Z4 | R | R13-2 | Z2 | F |

### 3.2 Effects of the fault type

3.2.1 Single phase to ground fault in line 12

When single phase to ground fault (a-g) occurs in middle of line 12, the pre-estimated zones of all relays are shown in Table 7.

Table7 pre-estimated fault zone for all relays for single phase fault in line 12

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z1 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z4 | R | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | F | R11-1 | Z4 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | R | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z1 | F | R19-1 | Z4 | R |
| R5-2 | Z4 | R | R12-2 | Z1 | F | R19-2 | Z4 | F |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | R |
| R6-2 | Z4 | F | R13-2 | Z1 | F | R20-2 | Z4 | F |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z4 | R |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z1 | F |

From Table 7, the fault is at the middle 60% of line 12 because the two relays at the ends of the line 12 see the fault in zone 1 in forward direction. The suspected relays are R3-1,R3-2,R12-1,R12-2,R13-1,R13-2,R19-1,R19-2,R20-1,R20-2,R21-1 and R21-2. The modified and final fault zones for the suspected relays are obtained as in Table 8.

Table 8 Pre-estimated, Modified and Final fault zones for single phase fault in line 12

| Relay | Pre-estimated | modified fault zone | final fault zone |
|---|---|---|---|
| R3-1 | Z1-F | Z1-F | Z2-F |
| R3-2 | Z4-R | Z1-R | Z4-R |
| R12-1 | Z1-F | Z1-F | Z1-F |
| R12-2 | Z1-F | Z1-F | Z1-F |
| R13-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z1-F | Z1-F | Z2-F |
| [redacted] | Z4-F | Z1-F | Z2-F |
| R19-2 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z4-F | Z1-F | Z2-F |
| R20-2 | Z4-R | Z1-R | Z4-R |
| R21-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z1-F | Z1-F | Z2-F |

By applying the rules of MSS, relays R13-2, R21-2, R3-1 which originally locates the fault as (Z1, Forward) will now locate it correctly as (Z2, forward).

### 3.3 Effect of fault location

When a three phase fault occurs in the end of line 12 near to relay R12-1, the pre-estimated zones of all relays are shown in Table 9.

Table 9 Pre-estimated fault zone for all relays for three phase fault in the end of line 12

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z2 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z4 | R | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | F | R11-1 | Z4 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | R | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z1 | F | R19-1 | Z4 | F |
| R5-2 | Z4 | R | R12-2 | Z2 | F | R19-2 | Z4 | R |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | F |
| R6-2 | Z4 | F | R13-2 | Z2 | F | R20-2 | Z4 | R |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z4 | R |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z2 | F |

From Table 9, the fault is close to the right end of line 12 because the relay at the left end of the line 12 (R12-2) sees the fault in zone 2 at forward direction and the relay at the right end of the line 12 (R12-1) sees the fault in zone 1 at forward direction. The suspected relays are R3-1,R3-2,R12-1,R12-2,R13-1,R13-2,R19-1,R19-2,R20-1,R20-2,R21-1 and R21-2. The modified and final fault zones for the suspected relays are obtained as in Table 10.

Table 10 pre-estimated, modified and final fault zones for three phase fault in the end of line 12

| Relay | Self pre-estimation | modified fault zone | final fault zone |
|---|---|---|---|
| R3-1 | Z2-F | Z1-F | Z2-F |
| R3-2 | Z4-R | Z1-R | Z4-R |
| R12-1 | Z1-F | Z1-F | Z1-F |
| [redacted] | Z2-F | Z2-F | Z1-F |
| R13-1 | Z4-R | Z1-R | Z4-R |
| R13-2 | Z2-F | Z1-F | Z2-F |
| R19-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z4-F | Z1-F | Z2-F |
| [redacted] | Z4-F | Z1-F | Z2-F |
| R20-2 | Z4-R | Z1-R | Z4-R |
| R21-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z4-F | Z1-F | Z2-F |

From Table 10, relay R12-2 initially locates the fault incorrectly in Zone-2 (pre-estimation) as the fault is very close to the remote bus. Comparing the two modified fault zones: (Z2, Forward) calculated at relay R12-2 with (Z1, Forward) calculated at relay R12-1 results in the final zone (Z1, Forward) at both sides according to rule 1. Consequently, relay R12-2 identifies the fault in zone 1 and hence, trips instantaneously. Zones of R19-2, R20-1 and R21-2, marked cells in Table 10, are also corrected.

### 3.4 Effect of multiple fault

Two simultaneous faults (three phase to ground) occur in the middle of lines 12 and 3. Pre-estimation zones of all relays are shown in Table 11.

Table11 Pre-estimated fault zone for all relays for two simultaneous faults in the middle of lines 12 and 3

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z1 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z1 | F | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | F | R11-1 | Z4 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | R | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z1 | F | R19-1 | Z4 | R |
| R5-2 | Z4 | R | R12-2 | Z1 | F | R19-2 | Z4 | F |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | R |
| R6-2 | Z4 | F | R13-2 | Z3 | F | R20-2 | Z4 | F |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z4 | R |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z3 | F |

As can be noted from Table 11, two faults are located. The first is at the middle 60% of line 12 because the two relays of line 12 see the fault in zone 1 in forward direction. The second is at the middle 60% of line 3 because the two relays of line 3 see the fault in zone 1 in forward direction. Relays R3-1, R3-2, R12-1, R12-2, R13-1, R13-2, R19-1, R19-2, R20-1, R20-2, R21-1 and R21-2 are suspected. The modified and final fault zones for these suspected relays are obtained as in Table 12.

Table 12 pre-estimated, modified and final fault zones for two simultaneous faults in the middle of lines 12 and 3

| Relay | Self pre-estimation | modified fault zone | final fault zone |
|---|---|---|---|
| R3-1 | Z1-F | Z1-F | Z1-F |
| R3-2 | Z1-F | Z1-F | Z1-F |
| R12-1 | Z1-F | Z1-F | Z1-F |
| R12-2 | Z1-F | Z1-F | Z1-F |
| R13-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z3-F | Z1-F | Z2-F |
| R19-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z4-F | Z1-F | Z2-F |
| R20-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z4-F | Z1-F | Z2-F |
| R21-1 | Z4-R | Z1-R | Z4-R |
| [redacted] | Z3-F | Z1-F | Z2-F |

By applying the MSS, relays (R13-2, R21-2) which originally locate the fault as (Z3, Forward) will now locate it correctly as (Z2, forward). Relays (R20-2, R19-2) which originally locate the fault as (Z4, Forward) will now locate it correctly as (Z2, forward).

### 3.5 Effect of fault resistance

3.5.1 Three phase to ground fault in middle of line 12 with fault resistance $R_f < 15\ \Omega$

Pre-estimation zones of all relays are shown in Table 13.

Table13 pre-estimate fault zone of all relays for three phase to ground fault in middle of line 12 with fault resistance $R_f < 15\ \Omega$

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z2 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z4 | R | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | R | R11-1 | Z4 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | F | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z1 | F | R19-1 | Z4 | R |
| R5-2 | Z4 | R | R12-2 | Z1 | F | R19-2 | Z4 | F |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | R |
| R6-2 | Z4 | F | R13-2 | Z3 | F | R20-2 | Z4 | F |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z4 | R |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z3 | F |

From Table 13, the fault is at the middle 60% of line 12 because the two relays at the end of the line 12 see the fault in zone 1 at forward direction. The suspected relays are R3-1, R3-2, R12-1, R12-2, R13-1, R13-2, R19-1, R19-2, R20-1, R20-2, R21-1 and R21-2. The modified and final fault zones for the suspected relays are obtained as in Table 14.

Table 14 Pre-estimated, modified and final fault zone for 3 phase fault in line 12, $R_f < 15\ \Omega$

| Relay | Self pre-estimation | modified fault zone | final fault zone |
|---|---|---|---|
| R3-1 | Z2-F | Z1-F | Z2-F |
| R3-2 | Z4-R | Z1-R | Z4-R |
| R12-1 | Z1-F | Z1-F | Z1-F |
| R12-2 | Z1-F | Z1-F | Z1-F |
| R13-1 | Z4-R | Z1-R | Z4-R |
| R13-2 | Z3-F | Z1-F | Z2-F |
| R19-1 | Z4-R | Z1-R | Z4-R |
| R19-2 | Z4-F | Z1-F | Z2-F |
| R20-1 | Z4-R | Z1-R | Z4-R |
| R20-2 | Z4-F | Z1-F | Z2-F |
| R21-1 | Z4-R | Z1-R | Z4-R |
| R21-2 | Z3-F | Z1-F | Z2-F |

By applying the MSS, relays (R13-2, R21-2) which originally locate the fault as (Z3, Forward) will now locate it correctly as (Z2, forward). Relays (R20-2, R19-2) which originally locatc the fault as (Z4, Forward) will now locate it correctly as (Z2, forward).

3.5.2 Three phase to ground fault in middle of line 12 with fault resistance $R_f \geq 15\ \Omega$

Pre-estimation zones of all relays are shown in Table 15.

Table 15 pre-estimate fault zone of all relays for three phase to ground fault in middle of line 12 with fault resistance $R_f \geq 15\ \Omega$

| Relay | Z | D | Relay | Z | D | Relay | Z | D |
|---|---|---|---|---|---|---|---|---|
| R1-1 | Z4 | R | R8-1 | Z4 | R | R15-1 | Z4 | F |
| R1-2 | Z4 | F | R8-2 | Z4 | F | R15-2 | Z4 | R |
| R2-1 | Z4 | F | R9-1 | Z4 | F | R16-1 | Z4 | F |
| R2-2 | Z4 | R | R9-2 | Z4 | R | R16-2 | Z4 | R |
| R3-1 | Z4 | F | R10-1 | Z4 | F | R17-1 | Z4 | R |
| R3-2 | Z4 | R | R10-2 | Z4 | R | R17-2 | Z4 | F |
| R4-1 | Z4 | R | R11-1 | Z4 | F | R18-1 | Z4 | F |
| R4-2 | Z4 | F | R11-2 | Z4 | R | R18-2 | Z4 | R |
| R5-1 | Z4 | F | R12-1 | Z4 | F | R19-1 | Z4 | R |
| R5-2 | Z4 | R | R12-2 | Z4 | F | R19-2 | Z4 | F |
| R6-1 | Z4 | R | R13-1 | Z4 | R | R20-1 | Z4 | R |
| R6-2 | Z4 | F | R13-2 | Z4 | F | R20-2 | Z4 | F |
| R7-1 | Z4 | R | R14-1 | Z4 | R | R21-1 | Z4 | R |
| R7-2 | Z4 | F | R14-2 | Z4 | F | R21-2 | Z4 | F |

It is observed from Table 15 that all relays in the network sce the fault in zone 4. Therefore, no fault can be detected or located, i.e. the situation points to no fault conditions. This is due to the high value of the fault resistance. Hence the MSS can not progress any more. More rigorous technique is required to determine the pre-estimate zone of the relays considering high fault resistance. Then MSS can work properly.

### 3.6 Dealing with communication failure

A general feature of the MSS is that in case of a communication failure, the protection system is not affected since the relay automatically responds with the traditional setting rules.

Since some relays in the proposed scheme receive local information from more than one relay (e.g., Relay R19-2 in Table 3), there is a probability of lost information.

In order to evaluate the effect of lost information, Table 3 was chosen as an example. The modified fault zone at station R19-2 will not be affected by missing any data from the local relays except for the data from relay R12-2 because it is the relay with the smallest zone number. In case of lost information from R12-2, the modified fault zone at the station R19-2 will be (Z4,F) instead of (Z1,F). However, the final decision will not be affected since the modified fault zone at the remote end station R19-1 is correctly estimated.

The worst condition in that case is to lose two specific data: The data from relay R12-2 and, at the same time, to lose the data from relay R12-1, which is a complex assumption with very low probability. Even with such remote possibility, the MSS gives a similar response to the traditional strategy.

## 4. Conclusion

A proposed strategy for the distance relay setting is introduced. The determination of the fault zone by the MSS is based on data shared locally with other distance relays at the same substation. Also, a command from the distance relay on the other end of the protected line is needed. The latter is transmitted using any existing teleprotection system. Based on analyzing this information, the relay decides the proper fault zone.

Sharing data in the MSS eliminates the effect of voltage and current measuring errors. The MSS succeeds in solving many distance relays backup setting problems (e.g., the problem of a long line following a short line or vice-versa and parallel lines). The improvement of protection performance using the MSS has been verified for an Egyptian transmission network under different fault conditions. The application of the MSS would provide enhanced performance for distance protection to mostly avoid maloperation. Besides, it can determine the faulty line or lines and locate precisely the faulty point on the line. This will help in lowering the fault locating and repair time.

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