A new interval approach for setting the distance relay zones to achieve perfect selectivity and maximum sensitivity

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Abstract--In this paper, an interval approach is presented to achieve perfect selectivity and maximum sensitivity in distance relay zones, considering uncertainties. For this purpose, first, the uncertainties affecting the settings of the three zones of a distance relay are discussed. Then, by using the Monte-Carlo simulation, the uncertainties are modelled and the impedances seen by the distance relay are obtained for internal and external faults of the protection zones. Under such conditions, the impedance seen by the relay is modelled as interval impedance for each zone of the relay. With interval impedance being known, an upper and a lower bound are obtained for each zone of the relay. Then, the settings of each zone are determined in such a way that at first, perfect selectivity is achieved between different zones of distance relays and second, the sensitivity of each zone is maximized. The sensitivity and the selectivity of the distance relay zones are defined based on the protection philosophy of these zones. The proposed interval method is applied on a sample 8-bus system, and the advantages of the proposed approach in comparison with conventional methods of setting distance relay zones are shown.

Index Terms -Interval Impedance, Sensitivity, Coordination, Distance Relay, Monte-Carlo Simulation.

I. INTRODUCTION

DISTANCE relays are mostly used asprimary and backup protections in transmission and sub-transmission lines. Regardless of the distance relay characteristic's type, three protection zones are defined for this relay. In the conventional approach of setting the distance relay zones, the first zone is responsible for protecting 80 to 90 percent of the protected line, and the rest of the line is protected by the second zone of the relay. Furthermore, the reach setting of the third zone is determined in a way that it protects all the second adjacent lines as the backup protection. However, in most cases, the reach setting obtained fromconventional method will not result in perfect selectivity and maximum sensitivity. By measuring the voltage and current, the distance relay calculates the impedance seen from the relay location, and if theapparent impedance is less than the relay setting impedance, the relay will operate [1, 2]. Uncertainties such as lines or transformers outage, inaccuracy of CTs or PTs, saturation of CTs, fault resistance, fault location, variations of load, generation and etc. cause the measured values of current and voltage to be different from their actual values. This can cause mal-operation of the distance relay.

In [3], uncertainties such as line and generation unit outages, changing the network topology, and the errors of measuring devices have been modeled probabilistically. In [4], several types of relay operational characteristics have been considered for different system conditions to clear the fault caused by dynamic loads. In [5-7], the effect of branched lines on distance protection have been studied. In [8, 9], uncertainties have been modeled probabilistically, and by defining sensitivity and selectivity coefficients, the problem of setting the distance relay has been converted into an optimization problem. By solving this optimization problem, the optimal settings of the three zones of the distance relay have been achieved.

In this paper, uncertainties affecting the impedance seen by the distance relay are presented first. Then, by considering uncertainties, an interval impedance is defined for each zone and the Monte-Carlo simulation algorithm is used for calculating this interval impedance. Considering the interval impedance, an upper and a lower bound are obtained for reach setting of each zone of the distance relay. These bounds are determined in a way that perfect selectivity is achieved between the relay zones. Then, the upper bound is selected as the setting of that zone to obtain maximum sensitivity. The results obtained by implementing the presented approach on a sample 8-bus system show that, this approach has significantly increased the accuracy of protection.

The rest of this paper is organized as follows. In section 2, uncertainties affecting the impedance seen by the distance relay are introduced and their effects on relay operation are discussed. A new interval method for setting of protection zones (PZ) with presence of uncertainties is presented at

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section 3. Section 4 shows the results of applying the proposed approach to a sample power system. Reach setting of different protection zones, PZ1, PZ2 and PZ3 are shown for some relays and also, comparison is made between proposed and conventional approaches. Section 5 gives the conclusions.

II. UNCERTAINTIES AFFECTED THE OPERATION OF DISTANCE RELAY

If a fault occurs in a transmission line, the impedance seen by the distance relay is calculated based on the voltage and current measured by the measuring transformers as follows:

$$Z_R = \frac{V_R}{I_R} \tag{1}$$

In (1), V_R, I_R, and Z_R are the voltage, current, and impedance seen by the relay, respectively. In Figure 1, if a fault occurs at the point F_1, the impedance Z_R seen by the relay R_1 is equal to the impedance from point A to F_1. Considering uncertainties, the apparent impedance seen by the relay R_1 for the internal fault F_1 might be greater than the impedance of the line AB. Therefore, the relay might incorrectly detect a fault outside the line (loss of sensitivity). Similarly, a fault occurring at point F_2, might be incorrectly detected as a fault inside the line (loss of selectivity) by the relay.

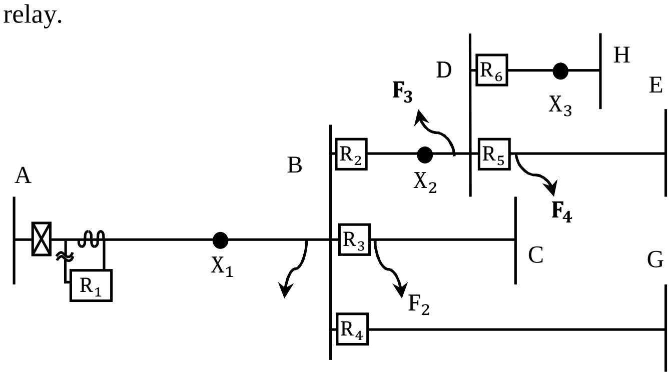

Figure 1. The single line diagram of a part of a power system

In this regard, at the next section, first the uncertainties will be discussed then, considering these uncertainties, the settings of different zones of the distance relay will be determined in a way that perfect selectivity and maximum sensitivity are obtained.

A. System uncertainties

The uncertainties affecting the fault impedance seen by the distance relay are divided into the following two main groups:

The first group includes the variations in the operating conditions of the system such as variations of load, generation and power factor, which affect the pre-fault load flow and cause the pre-fault bus voltages to change.

The second group includes changes in network topology (lines and generation units outage), fault resistance, the location of the fault, and inaccuracy in voltage and current transformers.

B. Interval impedance of the distance relay

The current and voltage measured by the distance relay under the conditions of uncertainties are not deterministic but rather they will change in a certain range. Under such conditions, the current and voltage measured by the relay are defined in an interval form as described by (2) and (3).

$$\tilde{V}_R = [V_R^{min} \quad V_R^{max}] \tag{2}$$

$$\tilde{I}_R = [I_R^{min} \quad I_R^{max}] \tag{3}$$

Where,

$\tilde{V}_R$, $\tilde{I}_R$: The interval voltage and current seen by the distance relay considering uncertainties, respectively.

V_R^{min}, V_R^{max} : The minimum and maximum values of measured voltage respectively.

I_R^{min}, I_R^{max}:The minimum and maximum values of measured current respectively.

Consequently, taking the uncertainties into account, the interval impedance seen by the relay will be as described by (4).

$$\tilde{Z}_R = \frac{\tilde{V}_R}{\tilde{I}_R} = [Z_R^{min} \quad Z_R^{max}] \tag{4}$$

Where,

$\tilde{Z}_R$: The interval impedance of the distance relay considering uncertainties.

Z_R^{min}, Z_R^{max}: The minimum and maximum impedance values seen by the relay.

The interval impedances are separately calculated for each zone of distance relay.

III. SETTING OF PROTECTION ZONES (PZ)

As shown in Figure 1, the relay R_1 in the beginning of the line AB is the primary protection of the line AB and the backup protection of the adjacent lines. The first protection zone (PZ1) of the relay R_1 must protect the line AB completely. Under ideal conditions, if the PZ1 setting of relay R_1 is equal to the magnitude of the impedance of the line AB, this goal will be achieved. However, the uncertainties discussed in the previous section affect the value of fault impedance measured by the relay R_1 and cause the reach of relay to increase or decrease.

In traditional approaches, to make sure that the relay will not operate for the fault that occurs outside the line (to achieve perfect selectivity), 80 to 90 percent of the line impedance is usually considered as the reach setting of PZ1 of distance relay. In the next, by considering uncertainties, the PZ1 setting of the relay is determined in a way that perfect selectivity and maximum sensitivity are achieved.

The protection philosophy of the PZ1 of the distance relay is defined in a way that first, the relay does not operate for faults outside the primary protection zone of the relay R1 i.e. outside the line AB (perfect selectivity), and second, the setting of the PZ1 needs to be as large as possible so that it can instantaneously protect a larger length of the line AB (maximum sensitivity).

Therefore, the highest relay setting impedance for the PZ1 without loss of selectivity is the best setting for this zone. In order to achieve perfect selectivity, the relay R_1 must not operate for faults in the adjacent lines. Therefore, the interval apparent impedance of the relay R_1 for faults occurring in different points of the adjacent lines in presence of all uncertainties is expressed by (5):

$$\tilde{Z}_{R,L_1} = [Z_{min,L_1} \quad Z_{max,L_1}] \tag{5}$$

Where Z_{R,L_1} is the interval impedance measured by the relay R_1 for a fault in the adjacent lines (L_1) considering uncertainties and Z_{min,L_1} and Z_{max,L_1} are its bounds.

To reach perfect selectivity, the relay must not operate for faults occurring in the adjacent lines. Thus, the reach setting impedance of the PZ1 of the relay R_1 needs to be less than or equal to $\tilde{Z}_{R,L_1}$. Therefore, the reach setting impedance of the first zone of the relay R_1 must be less than the smallest impedance seen by the relay in presence of all the uncertainties. On the other hand, to maximize the sensitivity, the protection zone of the relay R_1 must be selected as large as possible, therefore the highest reach setting which satisfies (6) must be selected as the reach setting of PZ1 of the relay as follows:

$$Z_{set1} < \tilde{Z}_{R,L_1} \rightarrow Z_{set1} < [Z_{min,L_1} \quad Z_{max,L_1}] \\ \rightarrow Z_{set1} \leq Z_{min,L_1} \tag{6}$$

$$Z_{set1} = Z_{min,L_1} \tag{7}$$

Since the fault impedance measured by the relay R_1 becomes higher as we move further from the bus B, the minimum fault impedance in the adjacent line (L_1) can be looked for just among the faults occurred at bus B in presence of all uncertainties. Therefore:

$$Z_{set1} = Z_{min,B} \tag{8}$$

Where, $Z_{min,B}$ is the minimum impedance measured by the relay R_1 for a fault at bus B, considering all the uncertainties.

A. Algorithm of PZ1 setting

To calculate the reach setting impedance of the PZ1 of the distance relay, the Monte-Carlo simulation shown in Figure 2 is proposed.

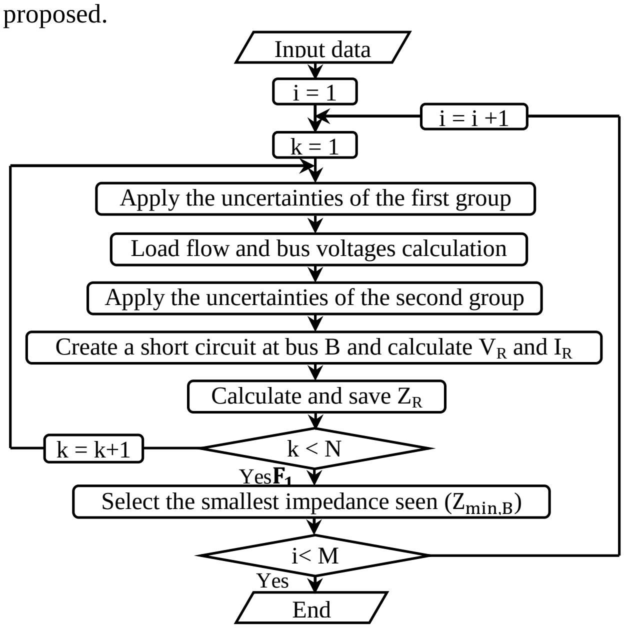

Figure 2. The proposed algorithm for determining the PZ1 setting of the distance relay

In this algorithm, irepresents the relay number and M is number of relays. Also, k denotes the iterations number and N is the maximum number of iterations of Monte-Carlo approach.

According to this algorithm, first, the uncertainties of the first group including variations of generation, load, and power factor are applied. Then, the load flow calculation is performed and the pre-fault bus voltages are obtained. Next, the uncertainties of the second group including the line and generation unit outage, fault type, fault resistance, fault location, and inaccuracies of current and voltage transformers are applied and the short circuit calculations are performed at remote bus of distance relay. Finally, the impedance seen by the relay (Z_R) is calculated. This process is repeated for N times. The above process is repeated for all the relays to calculate the reach setting impedance of the PZ1 of all the relays.

1) Maximum protected area of PZ_1

To compute the setting of PZ2 of the distance relay, the maximum length of protected transmission line that completely covers by PZ1 is required. At the next step, the furthest point of the protected line which is completely covered by the PZ1 (i.e. the sensitivity and selectivity up to that point is complete) is determined. Therefore, the furthest point of the protected line (point X_1 in Figure 1) must be determined in a way that the impedance seen by the relay $R_1$for a fault at all points before X_1, is less than the reachsetting impedance of the PZ1 of the relay R_1, considering all uncertainties.

$$\tilde{Z}_{R,l} = [Z_{min,l} \quad Z_{max,l}] \tag{9}$$

To do this, the interval impedance seen by relay R_1, at the point l in Figure 1, with considering uncertainties is determined as follows:

$$Z_{set1} > \tilde{Z}_{R,l} \rightarrow Z_{set1} > [Z_{min,l} \quad Z_{max,l}] \\ \rightarrow Z_{set1} \geq Z_{max,l} \tag{10}$$

If (10) is satisfied, the PZ1 of the relay R_1 will completely cover up to point l of transmission line AB in Figure 1.

$$Z_{max,l} = Z_{set1} \tag{11}$$

Since the maximum protected area of PZ1 is desired, the furthest point of the line AB which satisfies (11) (point X_1 in Figure 1) will determine the maximum length of the protected line covered by the PZ1 of the relay R_1. To obtain the point X_1, the algorithm shown in Figure 3 is proposed.

In this algorithm, the fault point l changes from the near-bus to the end-bus of the protected line. Then, the Monte-Carlo simulation process is performed and the largest impedance seen by the relay ($Z_{max,l}$) in presence of all uncertainties at point l is calculated. As long as $Z_{set1} > Z_{max,l}$, the length l increases. The point X_1 is determined as the end point of the PZ1 of relay R_1. It is obvious that up to the point X_1, the sensitivity of the first protection zone of the relay will be equal to 100 percent. This process is repeated for all the relays.

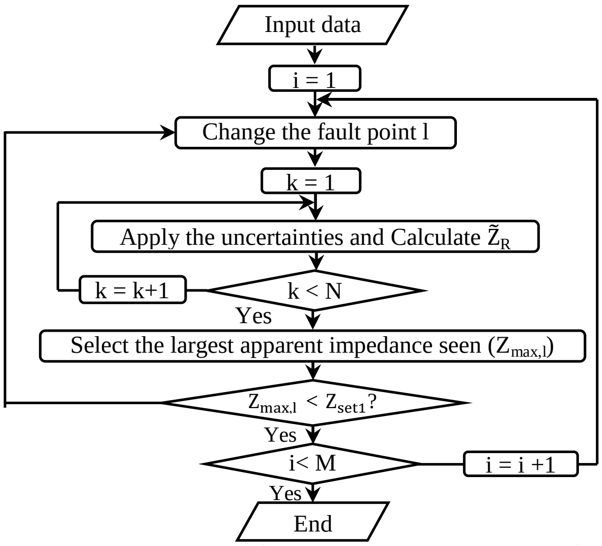

Figure 3. The proposed algorithm for determining the maximum area of PZ1

B. Algorithm of PZ2 setting

The protection philosophy of PZ2 is based on that first, it must cover the remaining protected lines. This means that the sensitivity of the relay is equal to 100 percent). Second, the protected area of PZ2 has no overlap with the PZ2 of the adjacent lines, and perfect selectivity is achieved (in other words, when a fault occurs within the PZ2 of adjacent lines, the PZ2 of the protected line must not operate).

According to Figure 1, if the point X_2 is the point covered by the PZ1 of the relay R_2 (located on the BD line), the maximum effective reach setting of the PZ2 of the relay R_1 must not exceed this point in any way. This means that for all the faults occurring beyond this point, in presence of all the uncertainties, the PZ2 of the relay R_1 mustn't operate.

Therefore, the impedance seen by the relay R_1 for the faults at the point X_2, in presence of all uncertainties, is defined by (12) in an interval manner.

$$\tilde{Z}_{R,X_2} = [Z_{min,X_2} \quad Z_{max,X_2}] \tag{12}$$

Where $\tilde{Z}_{R,X_2}$ is the interval impedance measured by the relay R_1 for a fault at the point X_2, considering all the uncertainties. Z_{min,X_2}andZ_{max,X_2} are The lower and upper bound of the interval impedance, respectively.

To achieve perfect selectivity, the reach setting of the PZ2 of the relay R_1 must be less than or equal to $\tilde{Z}_{R,X_2}$.

$$Z_{set2} \le \tilde{Z}_{R,X_2} \rightarrow Z_{set2} \le [Z_{min,X_2} \quad Z_{max,X_2}] \rightarrow Z_{set2} \le Z_{min,X_2} \tag{13}$$

Considering the fact that several lines might be connected to the protected line (lines BC, BG, and BD), equation (13) must be repeated for all these lines, and the smallest impedance must be considered. Therefore, the upper bound of the reach setting impedance of the PZ2 of the relay R_1 is obtained.

Furthermore, since the second protection zone of the relay R_1 must cover the rest of line AB, the reach setting of PZ2 must also be greater than the interval impedance seen by relay R_1 for a fault at bus B for all uncertainties:

$$Z_{set2} \ge \tilde{Z}_{R,B} \rightarrow Z_{set2} \ge [Z_{min,B} \quad Z_{max,B}] \rightarrow Z_{set2} \ge Z_{max,B} \tag{14}$$

Therefore, in (14) the lower bound of the reach setting impedance of the PZ2 of the relay R_1 is determined. According to (13) and (14), the reach setting of the PZ2 of the relay R_1 needs to be within the following interval:

$$Z_{max,B} \le Z_{set2} \le Z_{min,X_2} \tag{15}$$

Finally, to maximize the sensitivity, the reach setting of the second protection zone of the relay R_1 must be selected as high as possible. Therefore:

$$Z_{set2} = Z_{min,X_2} \tag{16}$$

To determine the Z_{min,X_2}, an approach similar to the Monte-Carlo simulation utilized in the previous section (Figure 2) can be used. The only difference is that first, the fault point must be the end point of the PZ1 of the relay R_2 (i.e. the point X_2). second, this algorithm has to be repeated for all the lines connected to the protected line until the smallest impedance seen by the relay R_1 for a fault at the point X_2 (i.e. Z_{min,X_2}), is obtained.

To calculate the reach setting of the PZ3 of the relay, the maximum length of the adjacent line which is covered by the PZ2 of the relay must be determined. Therefore, the point l is moved from bus B to the point X_2 of the line BD, and the furthest point up to which the second zone of the relay R_1 has a performance of 100 percent (the perfect sensitivity of the second zone), is determined as the maximum protected area of PZ2.

To do this, the fault location $(B \le l \le X_2)$ needs to be changed for all the uncertainties, and the interval impedance seen by the relay R_1 must be determined.

$$\tilde{Z}_{R,l} = [Z_{min,l} \quad Z_{max,l}] \tag{17}$$

Now, the maximum length of l for which the reach setting impedance of the PZ2 is greater than the interval impedance for a fault at the point l is determined. Therefore:

$$Z_{set2} \ge \tilde{Z}_{R,l} \rightarrow Z_{set2} \ge [Z_{min,l} \quad Z_{max,l}] \rightarrow Z_{set2} \ge Z_{max,l} \tag{18}$$

At a boundary point where the reach setting impedance of the relay (Z_{set2}) is equal to the maximum apparent impedance ($Z_{max,l}$), the maximum length covered by the PZ2 is defined (point X_3). Therefore:

$$Z_{max,l} = Z_{set2} \tag{19}$$

Similar to section 2-2, by carrying out the Monte-Carlo simulation algorithm, maximum length of the adjacent line covered by the PZ2 of the relay R_1 (point X_3) is calculated for all the lines connected to the protected line.

C. Algorithm of PZ3 setting

The protection philosophy of this zone is in a way that first, it completely covers all of the adjacent lines connected to the protected line (perfect sensitivity), as the backup protection. Second, it must have no miss-coordination with the PZ3 of the relay of the adjacent lines (perfect selectivity).

According to Figure 1, if the point X_3 is the maximum area covered by the second protection zone of the relay R_2, all of the fault impedances at points beyond X_3 must be outside the third protection zone of the relay R_1. The fault impedance measured by the relay R_1 for a fault at the point X_3 is defined in an interval manner by (20).

$$\tilde{Z}_{R,X_3} = [Z_{min,X_3} \quad Z_{max,X_3}] \tag{20}$$

Thus, to achieve perfect selectivity, the reach setting impedance of the PZ3 of the relay R_1 must be less than or equal to the interval impedance $\tilde{Z}_{R,X_3}$:

$$Z_{set3} \leq \tilde{Z}_{R,X_3} \rightarrow Z_{set3} \leq [Z_{min,X_3} \quad Z_{max,X_3}] \rightarrow Z_{set3} \leq Z_{min,X_3} \tag{21}$$

Therefore, the upper bound of the reach setting impedance of the PZ3 of the relay has been calculated. Considering the fact that several lines might be connected to the line BD (in Figure 1), therefore Z_{min,X_3} must be calculated for all the adjacent lines (DH and DE) and the lowest value must be considered as the upper bound of reach setting of PZ3.

On the other hand, since the third protection zone of the relay R_1 must cover the entire line AB together with all the adjacent lines (BD, BC, and BG), it has to be greater than the largest impedance of the fault occurred at the end-bus of the adjacent lines, considering all the uncertainties:

$$Z_{set3} \geq \tilde{Z}_{R,\{C,G,D\}} \rightarrow Z_{set3} \geq \left[Z_{min,\{C,G,D\}} \quad Z_{max,\{C,G,D\}}\right] \rightarrow Z_{set3} \geq Z_{max,\{C,G,D\}} \tag{22}$$

Where $\tilde{Z}_{R,\{C,G,D\}}$ is the interval impedance of the distance relay for a fault at buses C, G, and D.

Therefore, Z_{max} must be calculated for all the end-buses D, C, and G, and their largest value must be considered:

$$Z_{set3} \geq Z_{max,D} \tag{23}$$

Thus, the lower bound of the reach setting impedance of the PZ3 of the relay R_1 has been calculated. Therefore, considering (21) and (23):

$$Z_{max,D} \leq Z_{set3} \leq Z_{min,X_3} \tag{24}$$

Finally, to maximize the sensitivity, the third protection zone (PZ3) of the relay R_1 must be selected as large as possible, as follows:

$$Z_{set3} = Z_{min,X_3} \tag{25}$$

Using the Monte-Carlo simulation algorithm all the uncertainties are applied to the network, and the minimum impedance seen by the relay R_1 for a fault at points of X_3 (the end of the second protection zone of the relays of the adjacent lines) is calculated.

Also, the maximum area covered by the PZ3 of the relay of R_1 can be calculated similar to section 2-2.

IV. Numerical Results

To apply the proposed approach, a sample 8-bus network which is shown in Figure 4 is used.

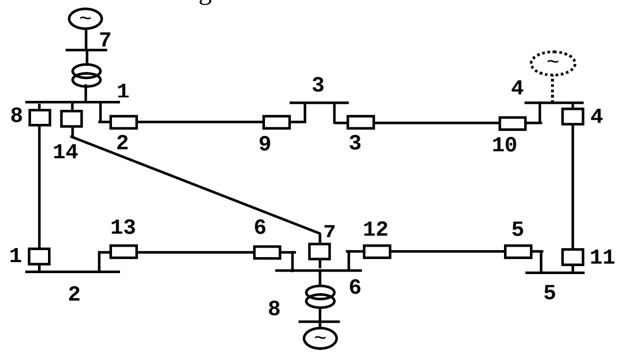

Figure 4. Single-Line diagram of the 8-bus test system

This network consists of 7 lines, 14 distance relays, and 2 generators installed at buses 1 and 8 to supply the loads.The generators and lines data are presented in Tables 1 and 2, respectively.

TABLE 1
The transient impedance of generators

Bus number	Resistance	Reactance
7	0.0	0.15
8	0.0	0.15

For this network, the measurement errors for CT and PT are considered to be equal to 5% and 2%, respectively with normal probability distributions function, and the average fault resistance is considered to be equal to 1 ohm with asymmetric Weibull probability distribution.

TABLE 2
The transmission line data of 8-bus network

Line number	From Bus	To Bus	Resistance	Reactance
1	1	2	0.0027	0.0333
2	1	3	0.0027	0.0333
3	3	4	0.0027	0.0300
4	4	5	0.0033	0.0300
5	5	6	0.0033	0.0300
6	2	6	0.0026	0.0300
7	1	6	0.0033	0.0333
8	7	1	0.0000	0.0400
9	8	6	0.0000	0.0400
10	0	4	0.0000	0.3750

Also, the annual load duration curve of this network has been presented in [10]. In Monte-Carlo simulation process, in each iteration, one point is selected from the annual load duration curve, and generation of units will change in proportion to this load. Then, by randomly selecting the power factor (asymmetric Weibull probability distribution between 0.8 and 0.95), the load flow is performed and the pre-fault bus voltages are determined. The number of iterations of Monte-Carlo simulation is considered to be 100000. In this paper, the reach setting of relay-14 is calculated. The reach settings of the other distance relays of the 8-bus network can be determined in a similar way.

A. Calculating the interval impedance

In this section, considering the uncertainties, the interval impedance seen by the distance relay 14 is calculated. First, the fault is created in the primary protected line of relay 14 (line 1-6). For this purpose, the algorithm proposed in Figure 2 is carried out for the relay 14 and the interval impedance ($\tilde{Z}_R$) is calculated for a fault at the end-bus of the primary line (Bus 6). The values of this impedance are presented in Table 3.

TABLE 3
THE INTERVAL IMPEDANCE OF THE RELAY 14 FOR A FAULT AT BUS 6

$\tilde{Z}_R$	
Z_R^{min}	Z_R^{max}
0.0278294	0.0420933

B. Reach setting of PZ1

To achieve perfect selectivity and to reach maximum possible sensitivity, the minimum interval impedance $\tilde{Z}_R$(according to (8)) is selected as the reach setting of the PZ1 of the relay 14. Considering the fact that the PZ1 settings of the relays of the adjacent lines are required for calculating the reach setting of PZ2 of relay 14, the reach settings of relays 12 and 6 (relay of the adjacent lines) are similarly calculated by using the Monte-Carlo simulation process. The reach settings of PZ1 for relays 14, 12 and 6 are shown in Table 4.

TABLE 4
PZ1 SETTINGS OF RELAYS 14, 12 AND 6

Relay No	$\tilde{Z}_R$		Z_{set1}
	Z_R^{min}	Z_R^{max}	
14	0.0278294	0.0420933	0.0278294
12	0.0275607	0.0350347	0.0275607
6	0.0276278	0.0354780	0.0276278

Based on algorithm shown in Figure 3, to determine the maximum area completely covered by the PZ1 of relay 14, the fault location moves along line 1-6, and the maximum length for which the largest impedance seen by the relay 14 is equal to the PZ1 setting of this relay is determined. The results of performing this algorithm on relays 14, 12, and 6 are presented in Table 5.

TABLE 5
THE MAXIMUM AREA COMPLETELY COVERED BY THE PZ1

Relay No	14	12	6
Maximum covered area in percent	0.6643	0.7770	0.7488

For example, for a fault within the beginning 66% of line 1-6, considering all uncertainties, the PZ1 of the relay 14 will surely operate.

C. Reach setting of PZ_2

The interval impedance seen by the relay 14 for a fault at the end of the first protection zone of the relays of the adjacent lines (relays 12 and 6) is calculated. For this purpose, considering all the uncertainties, a fault is created within the PZ1 of relays 12 and 6 (within 77.7% and 74.8% of the lines 6-5 and 6-2, respectively) then, by using the Monte-Carlo iteration, the interval impedance seen by the relay 14 is calculated. The results are presented in Table 6.

According to (15), the minimum impedance is selected as the upper bound of the setting of the second zone of relay 14. The lower bound of the PZ2 setting for relay 14 is known according to the results presented in Table 3. To achieve the maximum sensitivity, the upper bound is selected.

TABLE 6
THE INTERVAL IMPEDANCE OF RELAY 14

Fault location	$\tilde{Z}_R$	
	Z_R^{min}	Z_R^{max}
End of the PZ1 of the relay 12	0.098712	0.140937
End of the PZ1 of the relay 6	0.085414	0.133216

The above process is repeated for the relays 12 and 6, and the settings of the second zones of these relays are calculated and presented in Table 7. These settings will be used to determine the setting of the third zone of the relay 14.

TABLE 7
THE PZ2 SETTING OF THE RELAYS 14, 12 AND 6

Relay No	14	12	6
Z_{set2}	0.085414	0.0500281	0.0468227

The maximum area completely covered by the second zone of the relay 14 for each one of the lines 6-5 and 6-2, according to (19) are determined and the results are presented in Table 8.

TABLE 8
THE MAXIMUM AREA COMPLETELY COVERED BY THE PZ2 OF THE RELAY 14

Line Number	6-5	6-2
Maximum covered area in percent	0.3832	0.3410

Also, the (19) is repeated for the relays 12 and 6, and the end of the second protection zone of these relays are obtained and shown in Table 8.

TABLE 9
THE MAXIMUM AREA COMPLETELY COVERED BY THE SECOND ZONE OF THE RELAYS 12 AND 6

Line Number	12	6
Maximum area covered by second zone	0.5031	0.3094

D. Reach setting of PZ_3

In this section, the impedance seen by the relay 14 for a fault at the end of the second zone of the relay of the adjacent lines (relays 12 and 6), considering all the uncertainties, are calculated and presented in Table 10.

TABLE 10
THE INTERVAL IMPEDANCE OF RELAY 14

Fault location	$\tilde{Z}_R$	
	Z_R^{min}	Z_R^{max}
End of the PZ1 of the relay 12	0.2587487	0.4260065
End of the PZ1 of the relay 6	0.1607710	0.219847

The minimum impedance in Table 10 is selected as the upper bound of the PZ3 reach setting for relay 14. But in order to calculate the lower bound of PZ3, the largest impedance seen by relay 14 for a fault at the end-bus of the adjacent lines (buses 5 and 2) must be calculated according to Table 11.

TABLE 11
THE INTERVAL IMPEDANCE OF RELAY 14 FOR A FAULT AT THE END OF THE ADJACENT LINES

Fault location	$\tilde{Z}_R$	
	Z_R^{min}	Z_R^{max}
Bus 5	0.130176	0.930568
Bus 2	0.128841	0.894350

Therefore, the setting impedance of the PZ3 of the relay 14 must satisfy the following equation:

$$0.0130176 \leq Z_{set3} \leq 0.1607710 \quad (26)$$

Thus, in order to achieve maximum sensitivity, the PZ3 setting of the relay 14 is selected as the upper bound:

$$Z_{set3} = 0.1607710 \quad (27)$$

The maximum area completely covered by the third zone of relay 14 is calculated and presented in Table 12.

TABLE 12
THE MAXIMUM AREA COMPLETELY COVERED BY THE PZ3 OF RELAY 14

Line Number	5-4	2-1
Maximum area covered by PZ3 of relay 14	0.2332	0.1710

Finally, the results related to the first, second, and third zones of relay 14 are summarized in Table 13.

TABLE 13
THE PROPOSED REACH SETTINGS OF DISTANCE RELAY 14

Protection zone	First	Second	Third
Setting of relay 14	0.027829	0.085414	0.160771

E. Comparison between proposed and conventional approach

In this section, according to the conventional approach, the settings of the first zones of the distance relays are considered to be equal to 85% of the protected line impedance.The settings of PZ1 of relays 14, 12 and 6 calculated by using the proposed and conventional methods are presented in Table 14.

TABLE 14
THE PZ1 SETTING OF RELAYS OBTAINED BY USING THE PROPOSED AND CONVENTIONAL APPROACHES

Relay No	Setting by proposed approach	Setting by conventional method
14	0.0278	0.02844
12	0.0275	0.02565
6	0.0276	0.02559

For relays 12 and 6, considering all the uncertainties, the proposed approach presents a larger impedance. Therefore, the sensitivity of the proposed approach is larger than that of the conventional approach. In other words, by using the setting of the proposed approach, the PZ1 of relay 12 protects a larger length of line 6-5 instantaneously without loss of selectivity, in comparison to the conventional approach.

But for the relay 14, the setting of the proposed approach is lower than that of the conventional approach. This means that if the setting of the conventional approach is used, relay-14 may operate for some external faults of the protected line. For example, supposed a fault that is created in the first 5% of the line 6-5 considering all the uncertainties and by using the Monte-Carlo process, the interval impedance seen by relay 14 is calculated to be $\tilde{Z}_R = [0.0281860 \quad 0.0321819]$.

Therefore, in the conventional approach, the setting impedance of the PZ1 of relay 14 isn't lower than the interval impedance ($Z_{set1}^{R14} \nleq \tilde{Z}_R$). Consequently, considering some of the uncertainties, relay 14 will operate for a fault within the first 5% of the adjacent line (line 5-6) and the selectivity of the PZ1 of relay 14 will be lost.

V. CONCLUSION

In this paper, an interval approach is presented to model the uncertainties and compute the setting of distance relay. By completely modeling the uncertainties using the Monte-Carlo simulation process, the interval impedance seen by the distance relay for faults inside and outside of protected line are obtained. In this approach, the settings are determined in a way that, perfect selectivity and maximum sensitivity are achieved for all zones of the distance relay. The proposed approach is applied on an 8-bus network and the settings of the first, second, and third zones are determined for one of the relays of this network. A comparison made between the results of the proposed approach and those of the conventional approach showed that the settings of the proposed approach have resulted in perfect selectivity and maximum sensitivity. While, in some cases, the settings of the conventional approach have caused loss of selectivity, and in some other cases haven't resulted in maximum sensitivity.

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