Coordination of directional overcurrent and distance relays based on nonlinear multivariable optimization

Tahseen Ali Abd Almuhsen¹, Ahmed Jasim Sultan²
¹,²Electrical Engineering Technical Collage, Middle Technical University, Iraq
¹,²Department of Electrical Power Engineering Techniques, Middle Technical University, Iraq

ABSTRACT

To ensure stability, security, and protection of electrical equipment from the damage the suitable coordination must be made in interconnected networks. In this paper, the nonlinear multivariable optimization techniques have been used with different performance indexes: Sequential quadratic programming (SQP), Sequential quadratic programming legacy (SQP-Legacy), Interior-Point and Active-Set for IEEE-8 bus test system. This system consists of twenty-eight protective relays divided into fourteen directional overcurrent relays (DOCR) and fourteen distance relays (DR). It has been tested in the ETAP environment to obtain three-phase short circuit current at the near and far end faults and operating time for all DOC relays for near-end fault as well as test the second zone time for distance relays (TZ2) with pilot signal (WP) and without pilot signal (WOP) of the proposed algorithm was used to reduce overall operating time of DOC relays and obtain optimal values for time multiplier setting (TMS) and TZ2 with the different coordination time interval (CTI) between main and backup relays. The simulation results were validated in ETAP program prove that the effectiveness of the Active-Set to minimize the TMS and TZ2 for the system.

Keywords: Directional overcurrent relay, Distance relay, Nonlinear multivariable optimization, Pilot protection

1. INTRODUCTION

Protective devices are the watchful eye on the protection of electrical equipment in case of any sudden fault occurred whereby isolated as fast as possible. Commonly distance protection relays are applied as the main protection in high and extra high voltage systems. While directional overcurrent relays are applied as the main protection in medium and low voltage systems and as a backup in high and extra high voltage systems.

Protection relays should be capable to isolate any fault in the network as early as possible so that to reach these goals, coordination between protection relays should be executed [1]. When taking into consideration main and backup relays together are distance protection relays, should be calculated as impedance for three zones as well as take all thing considered of interconnected grids such as the generators and transmission lines in service or out of service [2, 3]. There are three sets of coordination problems between DR and DOCR should be determined. These parameter sets are starting current setting (I_{set}), time setting multiple (TSM set) in DOCR and timer of the second zone (TZ2 set) of DR [4, 5].

To get a reliability in the power system should have a suitable setting to each relay, so protection relays should have respective specifications such as speed, selectivity and the sensitivity [6-9]. Conventionally, the protection devices engineers spend more time carry out calculation and employ graphics to coordinate between protection relays with technical constraints. The problem is appearing more difficult with large interrelated transmission grids [10].

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Presently, the optimization techniques have been used to coordinate between main and backup DOCR as well as between DR and DOCR. Also, it can be resolve constraints after identifying them between main and backup protective relays [10-16]. However, pilot protection has been used to decrease the tripping time of a transmission line [17]. Therefore, the total tripping time reduce from 0.4 sec to 0.04 sec, due to communication signal which sends between distance relays that be placed on the same transmission line from both sides [18].

In this paper, a nonlinear multivariable optimization technique with four performance indexes (SQP, SQP-legacy, interior-point, and active-set) for IEEE eight bus system was used to obtain optimal value of (TMS) of DOCR and (TZ2) of DR with and without pilot protection.

2. PROBLEM FORMULATION

Any transmission line in power system contains a distance relay as the main protection and directional overcurrent relay as local backup protection as shown in Figure 1. There are three scenarios can be done to achieve coordination between protective relays: main DR with backup DR, main DOCR with backup DOCR, and DOC relay with DR.

Figure 2 shows coordination between main R1 and backup R2 DOCR protective relays for near-end and far-end fault with the following constraints:

\[ \text{TR2}(F1) - \text{TR1}(F1) \geq CTI1 \] (1)

\[ \text{TR2}(F2) - \text{TR1}(F2) \geq CTI1 \] (2)

Where:

- TR1(F1) - operating time of main DOCR in near-end fault.
- TR1(F1) - operating time of main DOC in far-end fault.
- TR2(F1) - operating time of backup DOCR in near-end fault.

Figure 1. DR with DOCR
TR2(F2) - operating time of backup DOCR in far-end fault.
CTI1 - coordination time interval between R1 and R2 relays.

Figure 3 shows coordination between main R3 DR with backup R2 DOCR as well as coordination between main R1 DOCR with backup R4 DR with the following constraints:

\[
\begin{align*}
TR4(F3) - TR1(F3) & \geq CTI2 \\
TR2(F4) - TR3(F4) & \geq CTI2
\end{align*}
\]

Where:
TR3(F4) – operating time for second zone of main DR at far-end fault.
TR4(F3) – operating time for second zone of backup DR at near-end fault.
CTI2 - coordination time interval between R4 and R1 relays as well as R2 and R3 relays.

2.1. Fitness Function for DR and Main DOCR

The fitness function formula as:

\[
MIN \ FF = \sum_{j=1}^{M} T_j + \sum_{i=1}^{N} TZ2_i
\]

Where:
FF – fitness function.
Tj - operating time for j\textsuperscript{th} DOC relays for near-end fault.
M - total number of DOC relays.
TZ2i – operating time for second zone j\textsuperscript{th} distance relays.
N – total number of Distance Relays.

2.2. TMS and Pickup Current Setting of DOCR

Time multiplier setting (TSM) is bounded between two value lower and upper bound to each relay, as well as pickup current setting (I\textsubscript{psj}) to each one depends on lower minimum fault current and max load current.

\[
TMS_j \text{ Min} \leq TMS_j \leq TMS_j \text{ Max}
\]

Where:
TMS\textsuperscript{Min} is minimum bound of TMS for j\textsuperscript{th} relays.
TMS\textsuperscript{Max} is maximum bound of TMS for j\textsuperscript{th} relays.

\[
IPS_j \text{ Max-load} \leq IPS_j \leq IPS_j \text{ Min-fault}
\]

Where:
IPS\textsuperscript{Max-load} – pickup current setting for max load.
IPS\textsuperscript{Min-fault} – pickup current setting for min fault.
According to the bounded value for TMS in equation (6) will be obtain the operating time in equation (1) and (2). In this study according to IEC standard, normal inverse characteristic curve have been used with the following equation [4]:

$$T = \left[ \frac{0.14}{I_{sc}/I_{ps}^2 - 1} \right] T_{MS}$$

(8)

T – operating time for each DOCR.
I_{sc} – secondary value for short circuit current, passing during relay coil.
I_{ps} – pickup current setting for each DOC relay.

3. PILOT PROTECTION

The role of pilot protection is to accelerate the tripping time between two DR relays at same line and that leads to decrease the total operating time as well as operating time for second zone of DR. The permissive under reach transfer trip (PUTT) signal used to accelerate the tripping time [19]. The PUTT philosophy can be shown in Figure 4.

The transmission line would be divided into three zones: first zone have 80% of protected line length with instantaneous operating time, second zone has impedance but the second zone setting 120% of line length impedance at operating time equal to 0.4, so use PUTT to accelerate trip when one of DR see the fault at the second zone (80% - 100%) will start the second zone and receive signal from the remote distance relay and collect in (AND GATE), send trip to local circuit breaker and Reduces trip time from 40 to 2-4 millisecond. Figure 3 will be as shown in Figure 5 the second zone for the main distance relay time will reduce to 0.04 second.

Figure 4. PUTT philosophy

Figure 5. Coordination between distance and DOC relays with pilot protection
4. NONLINEAR MULTIVARIABLE ALGORITHM

Figure 6 shows the flow chart for the nonlinear multivariable optimization for solve coordination problem between main and back up relays.

![Flowchart for proposed algorithm](image)

Figure 6. Flowchart for proposed algorithm

5. RESULTS AND DISCUSSION

The IEEE- eight bus system consists of seven transmission lines, two generators, two step-up transformers and extension network at bus four with 400 MVA short circuit [20]. Therefore, we have fourteen distance relays and fourteen DOC relays according to the number of transmission lines. The pick-up current setting and current transformer ratio data presented in Table 1.
Table 1. Pick Up Current and Current Transformer Ratio

| No of relay | Pick up setting (A) | Current transformer ratio | No of relay | Pick up setting (A) | Current transformer ratio |
|-------------|---------------------|---------------------------|-------------|---------------------|---------------------------|
| R1          | 1                   | 240                       | R8          | 2.5                 | 240                       |
| R2          | 2.5                 | 240                       | R9          | 2                   | 240                       |
| R3          | 2.5                 | 160                       | R10         | 2.5                 | 240                       |
| R4          | 2.5                 | 240                       | R11         | 2.5                 | 240                       |
| R5          | 1.5                 | 240                       | R12         | 2.5                 | 240                       |
| R6          | 2.5                 | 240                       | R13         | 1.5                 | 240                       |
| R7          | 0.5                 | 160                       | R14         | 0.5                 | 240                       |

In Table 2 used the ETAP program to obtain three-phase short circuit current for near and far-end faults and Figure 7 shows the test system.

Table 2. Three Phase Short Circuit Current for Near and Far End Faults

| Three phase close-in end fault | Three phase far end fault |
|--------------------------------|---------------------------|
| Primary Relay                  | Fault current (A) | Back up Relay | Fault current (A) | Primary Relay | Fault current (A) | Back up Relay (A) | Fault current (A) |
| R1                             | 3069                | R6            | 3069                | R1           | 935                | R6               | 935                |
| R2                             | 5459                | R1            | 935                | R2           | 3364               | R1               | 380                |
| R2                             | 5459                | R7            | 1775               | R2           | 3364               | R7               | 721                |
| R3                             | 3364                | R2            | 3364               | R3           | 2120               | R2               | 2120               |
| R4                             | 3659                | R3            | 2120               | R4           | 2337               | R3               | 969                |
| R5                             | 2337                | R4            | 2337               | R5           | 1176               | R4               | 1176               |
| R6                             | 5682                | R5            | 1176               | R6           | 3069               | R5               | 646                |
| R6                             | 5682                | R14           | 1758               | R6           | 3069               | R14              | 74*                 |
| R7                             | 4851                | R5            | 1176               | R7           | 1775               | R5               | 221*               |
| R7                             | 4851                | R13           | 927                | R7           | 1775               | R13              | 935*                |
| R7                             | 4851                | R7            | 1775               | R8           | 2838               | R7               | 74*                 |
| R8                             | 5667                | R7            | 1775               | R8           | 2838               | R9               | 575                |
| R8                             | 5667                | R9            | 1144               | R8           | 2838               | R9               | 1144               |
| R9                             | 2418                | R10           | 2418               | R9           | 1144               | R10              | 1144               |
| R10                            | 3756                | R11           | 2217               | R10          | 2418               | R11              | 1056               |
| R11                            | 3501                | R12           | 3501               | R11          | 2217               | R12              | 2217               |
| R12                            | 5434                | R13           | 927                | R12          | 3501               | R13              | 417                |
| R12                            | 5434                | R14           | 1758               | R12          | 3501               | R14              | 792                |
| R13                            | 2838                | R8            | 2838               | R13          | 927                | R8               | 927                |
| R14                            | 4828                | R1            | 935                | R14          | 1758               | R1              | 927*                |
| R14                            | 4828                | R9            | 1144               | R14          | 1758               | R9               | 192*               |

Symbol * shows the current which not reach to pick up current setting during passing in DOC relays.
Symbol # shows the current which passing during DOC relays but in reverse directional.

Figure 7. The test system

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In [20-25] the range of coordination time interval is (0.2 - 0.5) second. So the CTI₁ and CTI₂ in equation from 1 to 4 will be chosen equal to 0.2 seconds in case (1) and in case (2) CTI₁ =0.3 in equation 1 and 2 and CTI₂= 0.2 in equation 3 and 4 and the TMS has been bounded from 0.1 to 1.1 continuous for lower and upper bounds respectively to each relay. Choosing the zones timer setting for each distance relay is TZ₁=0, TZ₂=0.4, and TZ₃=0.8.

The test for the system has been done with four performance indexes for nonlinear multivariable optimization technique is sequential quadratic programming (SQP), sequential quadratic programming legacy (SQP-legacy), interior - point and active - set with pilot protection(WP) and without pilot protection (WOP). There are sixty-eight linear inequality constraints and twenty-eight variable, all these constraints during the test in MATLAB simulation have achieved. Table 3 shows the number of iterations and elapsed time to find the solution for the four algorithms which used with and without pilot protection for two cases 1 & 2.

### Table 3. The Nonlinear Multivariable Optimization with Different Performance Indexes for All Cases

| Algorithms          | No of iteration | Case(1) WP | WOP | TMS in sec | Case(2) WP | WOP | TMS in sec |
|---------------------|-----------------|------------|-----|-----------|------------|-----|-----------|
| SQP                 | 3               | 2.6684     | 2.2103 | 3          | 2.3007     | 2.707 |
| SQP-legacy          | 3               | 2.3874     | 2.3574 | 3          | 2.3285     | 2.5367 |
| Interior-point      | 13              | 4.2236     | 3.5995 | 14         | 4.2596     | 4.1416 |
| Active-set          | 2               | 2.1552     | 0.7059 | 2          | 2.2788     | 2.2292 |

According to results, the active-set performance index was the least time and least iterations to obtain optimal value of TMS for all DOC relays and TZ₂ for all distance relays with and without pilot signal protection in all cases.

All algorithms with and without pilot signal results the TMS of DOC relays from relay 1 to relay 14 and the second zone timer for distance relays from relay 15 to relay 28 as identical results for all cases. all these results for case 1 and 2 show in Table 4 and Table 5 with total minimum fitness function of near-end faults for DOC relays as well as the fitness function for distance relays at second zone respectively. The overall time for DOC relays reduced about 3.18 MS in case 1 and 4.77 MS in case 2 when tested with and without pilot protection.

### Table 4. TMS for DOC Relays with All Performance Indexes

| Relay | TMS for all performance indexes (sqp, sqp-legacy, active-set and interior point). | TMS for all performance indexes (sqp, sqp-legacy, active-set and interior point). |
|-------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| No of Relay | With pilot | Without pilot | Only with near end fault | No of Relay | With pilot | Without pilot | Only with near end fault |
| R1    | 0.1562 | 0.1562 | 0.1562 | R1    | 0.2343 | 0.2343 | 0.2343 |
| R2    | 0.1913 | 0.1913 | 0.1913 | R2    | 0.287 | 0.287 | 0.287 |
| R3    | 0.1751 | 0.1751 | 0.1751 | R3    | 0.2627 | 0.2627 | 0.2627 |
| R4    | 0.1375 | 0.1375 | 0.1375 | R4    | 0.2063 | 0.2063 | 0.2063 |
| R5    | 0.1357 | 0.1357 | 0.1357 | R5    | 0.2035 | 0.2035 | 0.2035 |
| R6    | 0.1465 | 0.1465 | 0.1465 | R6    | 0.2198 | 0.2198 | 0.2198 |
| R7    | 0.3623 | 0.3623 | 0.3623 | R7    | 0.5435 | 0.5435 | 0.5435 |
| R8    | 0.1261 | 0.1261 | 0.1261 | R8    | 0.1891 | 0.1891 | 0.1891 |
| R9    | 0.1447 | 0.1447 | 0.1447 | R9    | 0.217 | 0.217 | 0.217 |
| R10   | 0.131 | 0.131 | 0.1395 | R10   | 0.1965 | 0.1965 | 0.2092 |
| R11   | 0.1367 | 0.1367 | 0.1367 | R11   | 0.205 | 0.205 | 0.205 |
| R12   | 0.188 | 0.188 | 0.188 | R12   | 0.282 | 0.282 | 0.282 |
| R13   | 0.1081 | 0.1081 | 0.1081 | R13   | 0.1622 | 0.1622 | 0.1622 |
| R14   | 0.3570 | 0.3570 | 0.3570 | R14   | 0.5355 | 0.5355 | 0.5355 |
| ΣRj   | 7.0615 | 7.0615 | 7.0933 | ΣRj   | 10.5923 | 10.5923 | 10.640 |

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The operating time for DOC relays in Matlab and ETAP simulation as well as the second zone timing and the timing of third zone will be (TZ2 + 0.4) shown in Table 6 and represent as a bar chart in Figure 8 for case 1 and Table 7 and Figure 9 for case (2).

### Table 6. The Operating Time for DOC Relays and Distance Relays (Case1)

| NO of Main relay | Time main DOCR in Matlab (sec) | Time main DOCR in ETAP (sec) | NO of backup relay | Time backup DOCR in Matlab (sec) | Time backup DOCR in ETAP (sec) | NO of relay | TZ2 distance Relay(sec) | TZ3 distance relay(sec) | CTI between Main and backup DOC relay | CTI between Main DOC relay and distance relay |
|-----------------|--------------------------------|-----------------------------|--------------------|---------------------------------|-------------------------------|-------------|------------------------|------------------------|--------------------------------------|---------------------------------------------|
| R1              | 0.4182                          | 0.418                       | R6                 | 0.6182                          | 0.616                         | R20         | 0.6182                | 1.0182                 | 0.2                                  | 0.2                                         |
| R2              | 0.5932                          | 0.592                       | R1                 | 0.7932                          | 0.792                         | R15         | 0.7932                | 1.1932                 | 0.2                                  | 0.2                                         |
| R3              | 0.5634                          | 0.563                       | R7                 | 0.7932                          | 0.792                         | R21         | 0.7932                | 1.1932                 | 0.2                                  | 0.2                                         |
| R4              | 0.5228                          | 0.525                       | R2                 | 0.7634                          | 0.762                         | R16         | 0.9228                | 1.3228                 | 0.2                                  | 0.3594                                       |
| R5              | 0.4983                          | 0.500                       | R3                 | 0.7228                          | 0.722                         | R17         | 0.7228                | 1.1228                 | 0.2                                  | 0.2                                         |
| R6              | 0.4461                          | 0.444                       | R4                 | 0.6983                          | 0.701                         | R18         | 0.6983                | 1.0983                 | 0.2                                  | 0.2                                         |
| R7              | 0.5928                          | 0.592                       | R14                | 0.7841                          | 0.784                         | R28         | 0.7841                | 1.1841                 | 0.338                                | 0.338                                       |
| R8              | 0.3842                          | 0.384                       | R13                | 0.7928                          | 0.795                         | R19         | 0.7928                | 1.1928                 | 0.3467                               | 0.3467                                       |
| R9              | 0.4907                          | 0.492                       | R7                 | 0.7932                          | 0.792                         | R27         | 0.7928                | 1.1928                 | 0.338                                | 0.338                                       |
| R10             | 0.4907                          | 0.491                       | R10                | 0.6486                          | 0.649                         | R23         | 0.7849                | 1.1849                 | 0.4007                               | 0.4007                                       |
| R11             | 0.5329                          | 0.534                       | R12                | 0.7225                          | 0.724                         | R25         | 0.7225                | 1.1225                 | 0.2318                               | 0.2318                                       |
| R12             | 0.5841                          | 0.584                       | R13                | 0.7928                          | 0.792                         | R26         | 0.7329                | 1.1329                 | 0.2                                  | 0.2                                         |
| R13             | 0.3591                          | 0.359                       | R8                 | 0.5591                          | 0.559                         | R22         | 0.7387                | 0.7387                 | 0.2                                  | 0.2                                         |
| R14             | 0.5849                          | 0.585                       | R9                 | 0.7849                          | 0.787                         | R23         | 0.7849                | 1.1849                 | 0.2                                  | 0.2                                         |

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Table 7. The Operating Time for DOC Relays and Distance Relays (Case2)

| NO of Main relay | Time main DOCR in Matlab (sec) | Time main DOCR in ETAP (sec) | NO of backup relay | Time backup DOCR in Matlab (sec) | Time backup DOCR in ETAP (sec) | NO of relay | TZ2 distance relay (sec) | TZ3 distance relay (sec) | CTI between Main and backup DOC relay | CTI between Main DOC relay and distance relay |
|------------------|-------------------------------|-----------------------------|-------------------|---------------------------------|---------------------------------|------------|------------------------|------------------------|-----------------------------------|---------------------------------------------|
| R1               | 0.6273                        | 0.627                       | R6                | 0.9273                          | 0.928                           | R20        | 0.8273                 | 1.2273                 | 0.3                               | 0.2                          |
| R2               | 0.8898                        | 0.890                       | R7                | 1.1898                          | 1.188                           | R15        | 1.0898                 | 1.4898                 | 0.3                               | 0.2                          |
| R3               | 0.8452                        | 0.846                       | R2                | 1.1452                          | 1.145                           | R16        | 1.2842                 | 1.6842                 | 0.3                               | 0.439                        |
| R4               | 0.7842                        | 0.783                       | R3                | 1.0842                          | 1.085                           | R17        | 0.9842                 | 1.3842                 | 0.3                               | 0.2                          |
| R5               | 0.7474                        | 0.746                       | R4                | 1.0474                          | 1.046                           | R18        | 0.9474                 | 1.3474                 | 0.3                               | 0.2                          |
| R6               | 0.6691                        | 0.670                       | R5                | 1.1893                          | 1.186                           | R19        | 1.0893                 | 1.4893                 | 0.3                               | 0.2                          |
| R7               | 0.8893                        | 0.889                       | R14               | 1.1762                          | 1.175                           | R28        | 1.0762                 | 1.4762                 | 0.3                               | 0.4073                       |
| R8               | 0.5764                        | 0.576                       | R7                | 1.1893                          | 1.186                           | R19        | 1.0893                 | 1.4893                 | 0.3                               | 0.2                          |
| R9               | 0.7361                        | 0.736                       | R10               | 0.973                           | 0.976                           | R24        | 0.9361                 | 1.3361                 | 0.2                               | 0.2369                        |
| R10              | 0.7361                        | 0.736                       | R11               | 1.0838                          | 1.084                           | R25        | 0.9838                 | 1.3838                 | 0.3                               | 0.3477                        |
| R11              | 0.7994                        | 0.799                       | R12               | 1.0994                          | 1.099                           | R26        | 0.9994                 | 1.3994                 | 0.3                               | 0.2                          |
| R12              | 0.8762                        | 0.876                       | R13               | 1.1893                          | 1.188                           | R27        | 1.0893                 | 1.4893                 | 0.3                               | 0.3131                        |
| R13              | 0.5387                        | 0.538                       | R8                | 0.8387                          | 0.838                           | R22        | 0.7387                 | 1.1387                 | 0.3                               | 0.2                          |
| R14              | 0.8773                        | 0.877                       | R1                | 1.1898                          | 1.188                           | R15        | 1.0898                 | 1.4898                 | 0.3                               | 0.2                          |
|                  |                               |                             | R9                | 1.1773                          | 1.177                           | R23        | 1.0773                 | 1.4773                 | 0.3                               | 0.2                          |

Figure 8. The operating time for DOC relays

Figure 9. The operating time for DOC relays and distance relays (case1) distance relays (case2)
The system has been tested in ETAP environment for all DOC relays during near-end fault to obtain the real operating time according to TMS curve for each relay. All relays chose same type Siemens type 7SJ64 numerical relay except R7 and R14 chose ABB relay type REF630, because of the operating time which obtained was wrong with Siemens relay the reason was the pick up current for Siemens type start from 0.5 A secondary current and the pick-up current for R7 and R14 is 0.5A that is lead to wrong results during test, while the ABB relay, the pick-up current start from 0.05A secondary current and this type more sensitive with pick up current for the R7 and R14 relays. One of these tests was at the transmission line (1-2) near from R1 for case 1 and 2 and the results of operating time for R1 and back up relays which had been sensitive by fault, shown in Figure 10 and Figure 11 respectively.

In case 1 the operating time for back up DOC relays and the second zone time for distance relays often will be trip in same time during fault, if the main zone 1 of distance relay and main DOC relay will failure and in case 2, if the main zone 1 and main DOC relay fails to clear faults the priority will be for second zone time for distance relay to clear fault before back up DOC relay.

Figure 10. The fault at the transmission line (1-2)
Figure 11. The fault at the transmission line (1-2) close-in of relay 1 (R1) (case 1) close-in of relay 1 (R1) (case 2)

6. CONCLUSION

In this paper, the operating time for the second zone of each distance relay set as independent value and the main aim was to obtain suitable coordination. Also, ETAP program has been used to obtain operating time for all DOC relays to validate it with the time which obtained from MATLAB simulation all operating times was identical and accurate in two cases 1 and 2.

So the independent setting for second zone operating time to each distance protection relay in the power systems is a better setting than a constant setting for all relays to ensure suitably coordination between DOC and distance relays. A nonlinear multivariable optimization technique was used with linear inequality constraints to obtain that with different performance indexes with and without pilot signal. So the active-set performance index in all cases with pilot signal was the best than other performance indexes to obtain optimal values at less time and less number of iterations.

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