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

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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.

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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].

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.

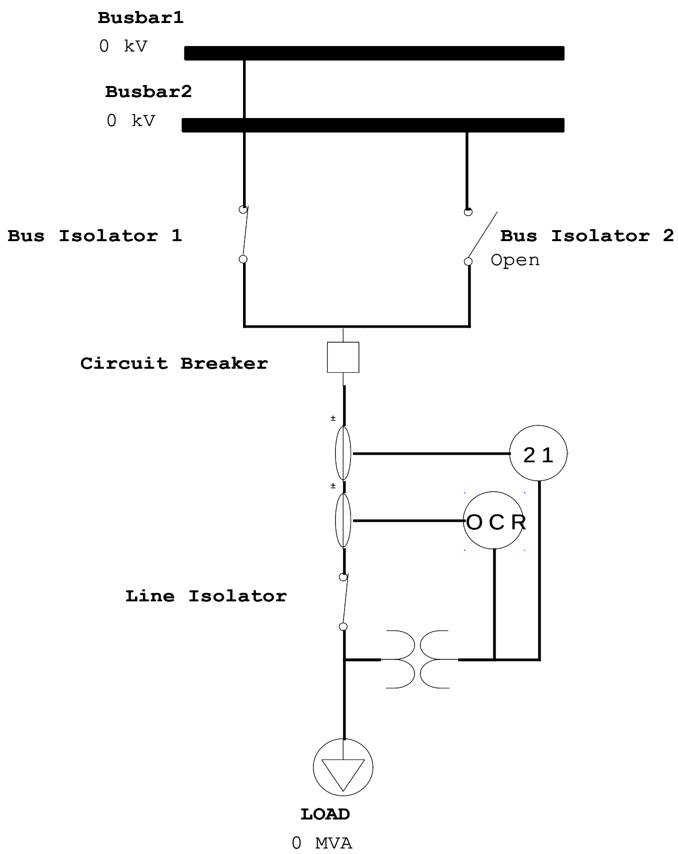

Figure 1. DR with DOCR

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

$$TR2(F1) - TR1(F1) \geq CTI1 \quad (1)$$

$$TR2(F2) - TR1(F2) \geq CTI1 \quad (2)$$

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.

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:

$$TR4(F3) - TR1(F3) \geq CTI2 \quad (3)$$

$$TR2(F4) - TR3(F4) \geq CTI2 \quad (4)$$

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.

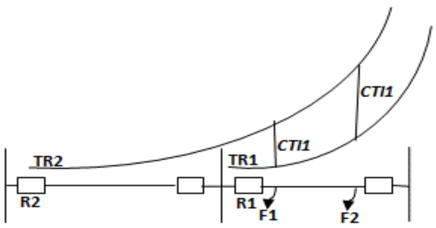

Figure 2. Coordination between main and backup DOCR

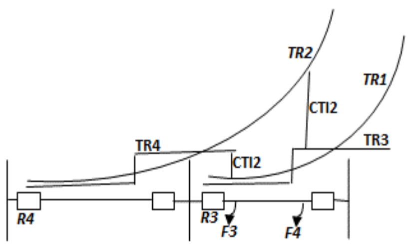

Figure 3. Coordination between DR and DOCRs.

2.1. Fitness Function for DR and Main DOCR

The fitness function formula as:

$$MIN\ FF = \sum_{j=1}^{M} T_j + \sum_{i=1}^{N} TZ2_i \quad (5)$$

Where:
FF – fitness function.
Tj - operating time for j^{th} DOC relays for near-end fault.
M - total number of DOC relays.
TZ2i – operating time for second zone i^{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_{ps}) to each one depends on lower minimum fault current and max load current.

$$TMS_j\ Min \leq TMS_j \leq TMS_j\ Max \quad (6)$$

Where:
TMS_j Min is minimum bound of TMS for j^{th} relays.
TMS_j max is maximum bound of TMS for j^{th} relays.

$$IPS_j\ Max\text{-}load \leq IPS_j \leq IPS_j\ Min\text{-}fault \quad (7)$$

Where:
IPS_j Max-load – pickup current setting for max load.
IPS_j 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]:

$$T = \left[\frac{0.14}{(\frac{Isc}{Ips})^{0.02} - 1} \right] TMS \tag{8}$$

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.

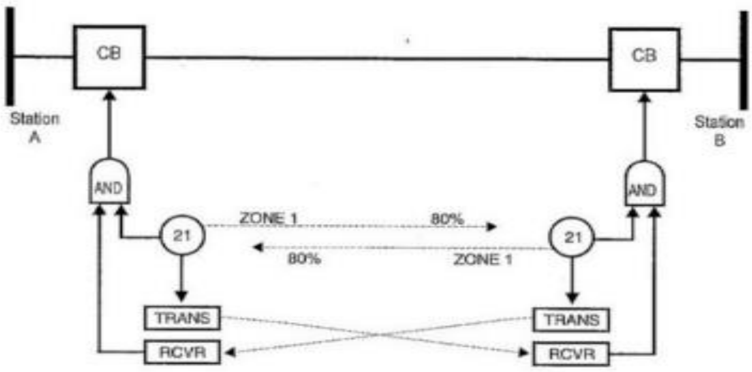

Figure 4. PUTT philosophy

The transmission line would be divided into three zons: first zone have 80% of protected line length with instantaneous operating time, second zone has imp 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.

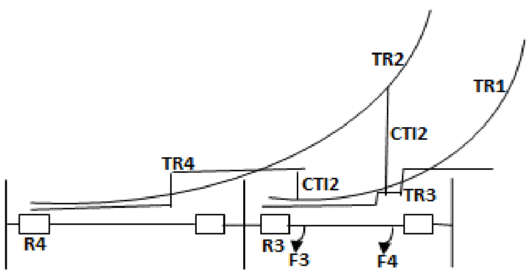

Figure 5. Coordination between distance and DOC relays with pilot protection

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.

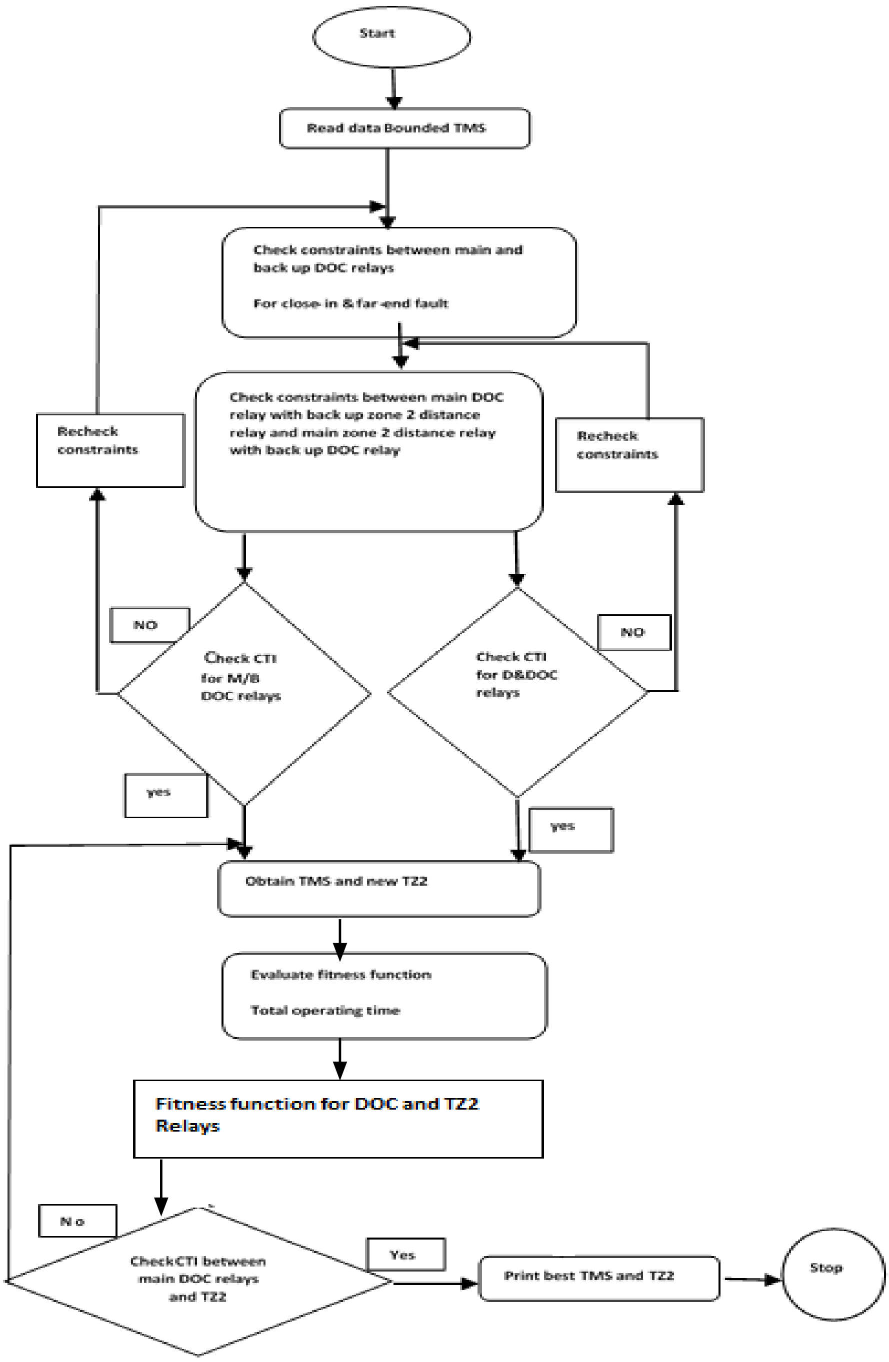

Figure 6. Flowchart for proposed algorithm

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	160
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	160

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 upRelay (A)	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#
R8	5667	R7	1775	R8	2838	R7	74#
R8	5667	R9	1144	R8	2838	R9	575
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 * shown 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.

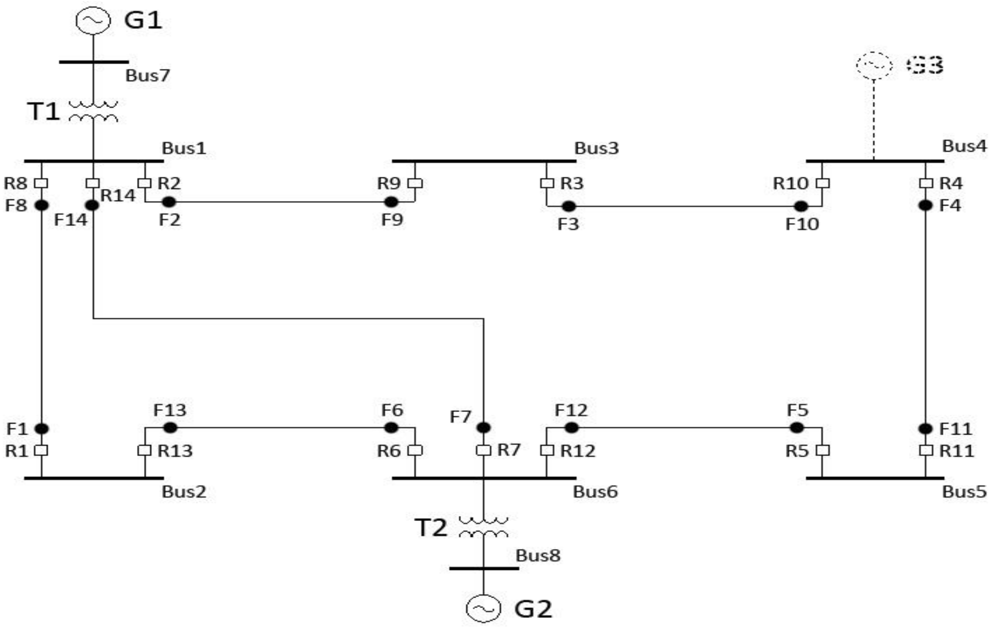

Figure 7. The test system

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) CTI =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	Case(1)				Case(2)			
	No of iteration		The solving time in (sec)		No of iteration		The solving time in (sec)	
	WP	WOP	WP	WOP	WP	WOP	WP	WOP
SQP	3	3	2.6684	2.2103	3	3	2.3007	2.2707
SQP-legacy	3	3	2.3874	2.3574	3	3	2.3285	2.5367
Interior–point	13	13	4.2236	3.5995	14	15	4.2596	4.1416
Active– set	2	2	2.1552	0.7059	2	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 the results of TMS for 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

TMS for all performance indexes (sqp, sqp-legacy, active-set and interior point). At CTI = 0.2 between (main and backup DOC relays) CASE (1)				TMS for all performance indexes (sqp, sqp-legacy, active-set and interior point). At CTI = 0.3 between (main and backup DOC relays) CASE (2)			
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
$\sum_{j=1}^{M} Tj$	7.0615	7.0615	7.0933	$\sum_{j=1}^{M} Tj$	10.5923	10.5923	10.640

Table 5. TZ2 for Distance Relays with All Performance Indexes

TZ2 for all performance indexes (Sqp, sqp-legacy, active-set and interior point). At CTI = 0.2 between (main and backup DOC relays) CASE (1)				TZ2 for all performance indexes (Sqp, sqp-legacy, active-set and interior point). At CTI = 0.2 between (main and backup DOC relays) CASE (2)			
No of Relay	With pilot	Without pilot	Without using far end fault, with and without pilot.	No of Relay	With pilot	Without pilot	Without using far end fault, with and without pilot.
R15	0.7932	0.7932	0.7932	R15	1.0898	1.0898	1.0898
R16	0.9228	0.9228	0.9228	R16	1.2842	1.2842	1.2842
R17	0.7228	0.7228	0.7228	R17	0.9842	0.9842	0.9842
R18	0.6983	0.6983	0.6983	R18	0.9474	0.9474	0.9474
R19	0.7928	0.7928	0.7928	R19	1.0893	1.0893	1.0893
R20	0.6182	0.6182	0.6182	R20	0.8273	0.8273	0.8273
R21	0.7932	0.7932	0.7932	R21	1.0898	1.0898	1.0898
R22	0.5591	0.5591	0.5591	R22	0.7387	0.7387	0.7387
R23	0.7849	0.7849	0.7849	R23	1.0773	1.0773	1.0773
R24	0.6907	0.6907	0.6907	R24	0.9361	0.9361	0.9361
R25	0.7225	0.7225	0.7225	R25	0.9838	0.9838	0.9838
R26	0.7329	0.7329	0.7329	R26	0.9994	0.9994	0.9994
R27	0.7928	0.7928	0.7928	R27	1.0893	1.0893	1.0893
R28	0.7841	0.7841	0.7841	R28	1.0762	1.0762	1.0762
$\sum_{i=1}^{N} TZ2i$	10.4084	10.4084	10.4084	$\sum_{i=1}^{N} TZ2i$	14.2126	14.2126	14.2126
Average TZ2	0.7435	0.7435	0.7435	*Average TZ2*	1.0152	1.0152	1.0152

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 main 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
			R7	0.7932	0.792	R21	0.7932	1.1932	0.2	0.2
R3	0.5634	0.563	R2	0.7634	0.762	R16	0.9228	1.3228	0.2	0.3594
R4	0.5228	0.525	R3	0.7228	0.722	R17	0.7228	1.1228	0.2	0.2
R5	0.4983	0.500	R4	0.6983	0.701	R18	0.6983	1.0983	0.2	0.2
R6	0.4461	0.444	R5	0.7928	0.795	R19	0.7928	1.1928	0.3467	0.3467
			R14	0.7841	0.784	R28	0.7841	1.1841	0.338	0.338
R7	0.5928	0.592	R5	0.7928	0.795	R19	0.7928	1.1928	0.2	0.2
			R13	0.7928	0.792	R27	0.7928	1.1924	0.2	0.2
R8	0.3842	0.384	R7	0.7932	0.792	R21	0.7932	1.1932	0.409	0.409
			R9	0.7849	0.787	R23	0.7849	1.1849	0.4007	0.4007
R9	0.4907	0.492	R10	0.6486	0.649	R24	0.6907	1.0907	0.1579	0.2
R10	0.4907	0.491	R11	0.7225	0.724	R25	0.7225	1.1225	0.2318	0.2318
R11	0.5329	0.534	R12	0.7329	0.733	R26	0.7329	1.1329	0.2	0.2
R12	0.5841	0.584	R13	0.7928	0.792	R27	0.7928	1.1924	0.2087	0.2087
			R14	0.7841	0.784	R28	0.7841	1.1841	0.2	0.2
R13	0.3591	0.359	R8	0.5591	0.559	R22	0.5591	0.9591	0.2	0.2
R14	0.5849	0.585	R1	0.7932	0.792	R15	0.7932	1.1932	0.2083	0.2083
			R9	0.7849	0.787	R23	0.7849	1.1849	0.2	0.2

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 main 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	R1	1.1898	1.188	R15	1.0898	1.4898	0.3	0.2
			R7	1.1898	1.189	R21	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	0.5202	0.4202
			R14	1.1762	1.175	R28	1.0762	1.4762	0.5071	0.4071
R7	0.8893	0.889	R5	1.1893	1.186	R19	1.0893	1.4893	0.3	0.2
			R13	1.1893	1.188	R27	1.0893	1.4893	0.3	0.2
R8	0.5764	0.576	R7	1.1898	1.189	R21	1.0898	1.4898	0.6134	0.5134
			R9	1.1773	1.177	R23	1.0773	1.4773	0.6009	0.5009
R9	0.7361	0.736	R10	0.973	0.976	R24	0.9361	1.3361	0.2369	0.2
R10	0.7361	0.738	R11	1.0838	1.084	R25	0.9838	1.3838	0.3477	0.2477
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	0.3131	0.2131
			R14	1.1762	1.175	R28	1.0762	1.4762	0.3	0.2
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	0.3125	0.2125
			R9	1.1773	1.177	R23	1.0773	1.4773	0.3	0.2

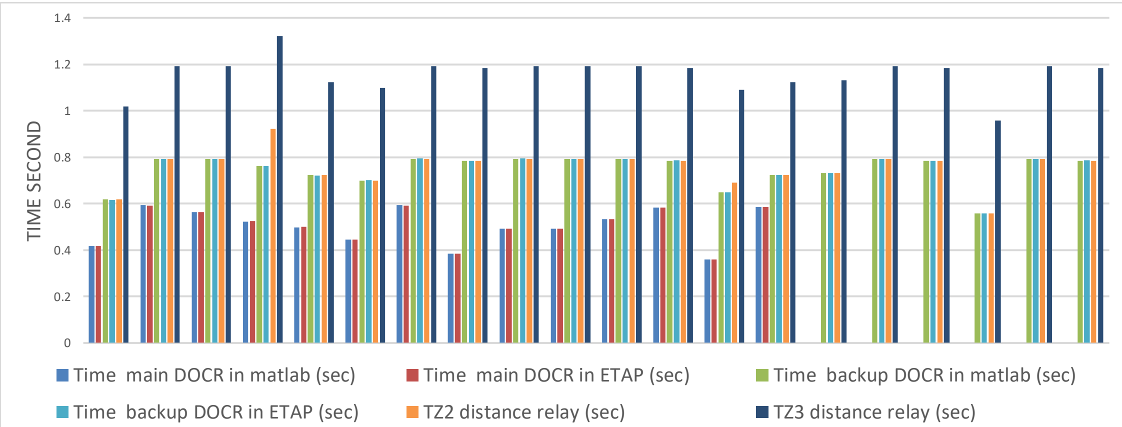

Figure 8. The operating time for DOC relays

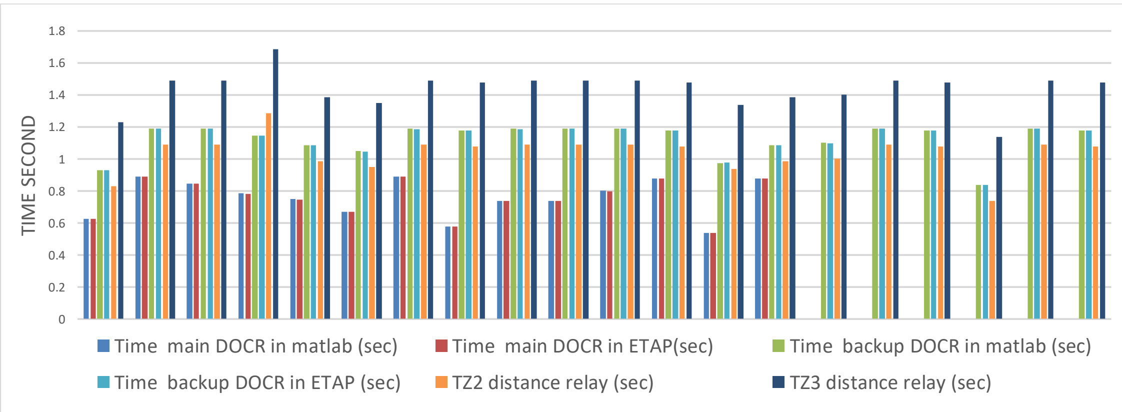

Figure 9. The operating time for DOC relays and distance relays (case1) distance relays (case2)

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.

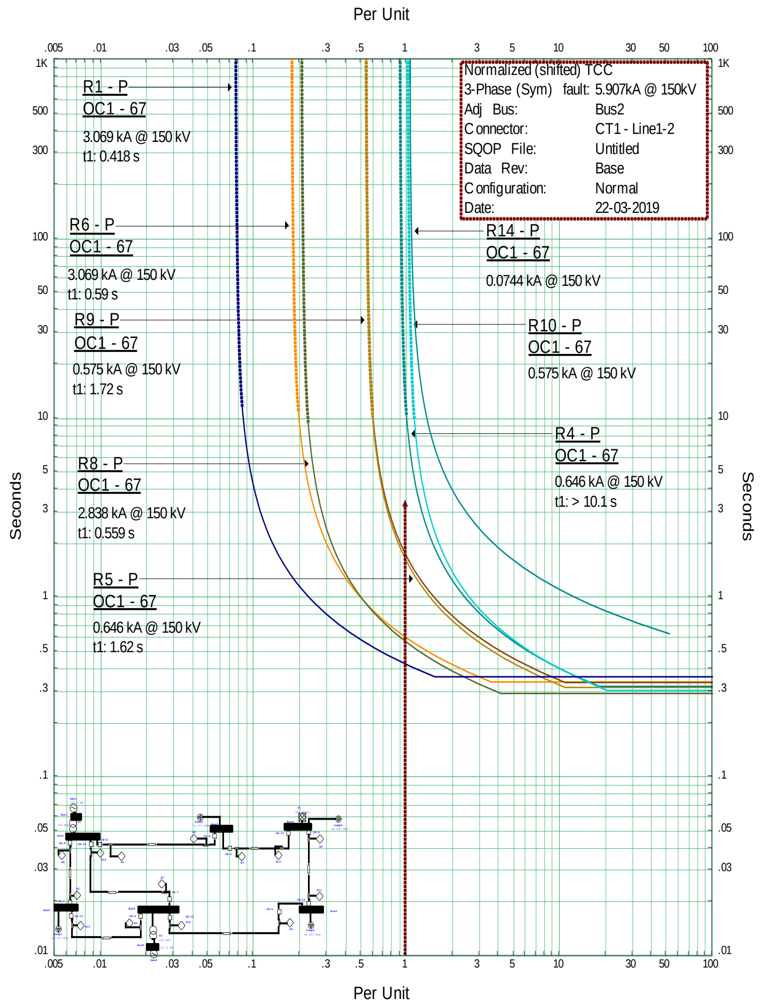

Figure 10. The fault at the transmission line (1-2)

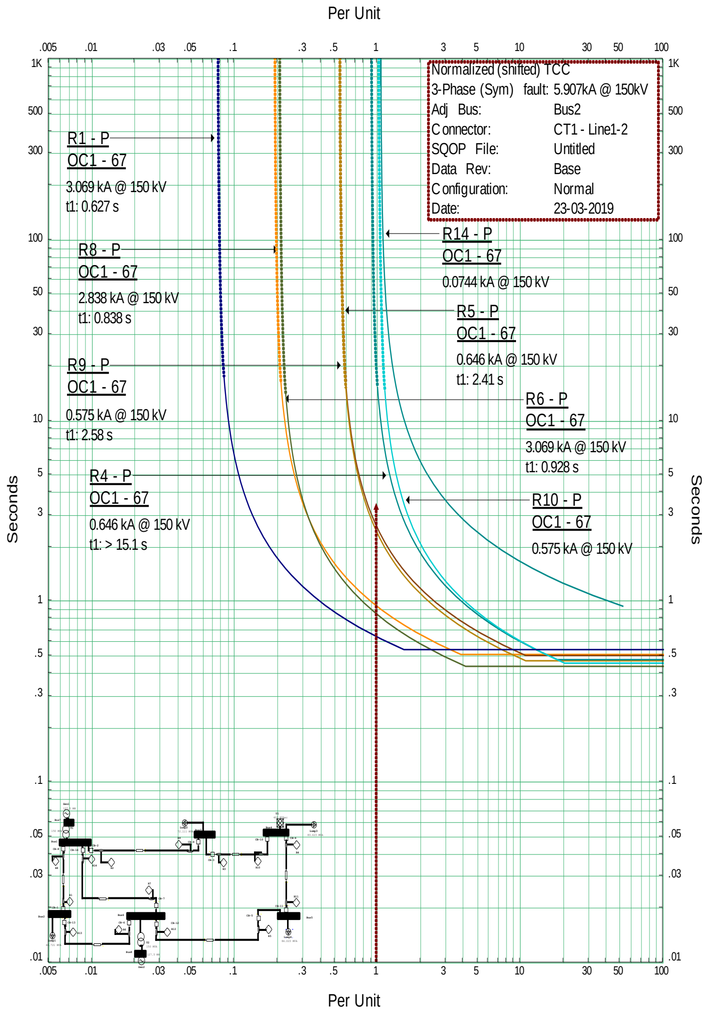

Figure 11. The fault at the transmission line (1-2) close-in of relay 1 (R1) (case 1) close-in of relay 1 (R1) (case 2)

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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