Protection Coordination with Static Security Assessment

Mahamad Nabab Alam
Department of Electrical Engineering
National Institute of Technology Warangal
Warangal–506004, India
mnalam@nitw.ac.in

***Abstract*—Protection coordination considering network security constraints is a challenging task. Power networks are designed to operate properly even under $N-1$ contingencies caused by the outage of some major components, such as power conductor, transformer, and generator. However, maintaining proper coordination among protective relays is difficult under such contingencies in interconnected power distribution networks. In this paper, the optimum protection coordination scheme of directional overcurrent relays, considering allowable $N-1$ contingencies, has been presented. This scheme provides a single setting-group of relays to provide proper protection coordination under all allowable contingencies in the system. This protection coordination problem has been formulated as a mixed-integer programming problem and solved using an interior-point method based algorithm. For selecting the allowable contingencies, a composite security index has been used. The effectiveness and suitability of the obtained settings have been demonstrated in the IEEE 14 bus test system.**

***Index Terms*—Coordination time interval, directional overcurrent relays, protection coordination, security assessment.**

I. Introduction

Maintaining a prespecified coordination time interval (CTI) between the operating times of primary and its corresponding backup relay is the inherent requirement for proper protection coordination among most protection schemes. The operation of the primary relay for a fault removes a tittle portion of the network. On the other hand, the backup relay operation for a fault removes a larger portion of the network unnecessary. Therefore, the protection scheme should allow its primary relay to clear the fault as quickly as possible. In case the primary relay fails to clear the fault, then their corresponding backup relays should take over the tripping command to open all circuit breakers associated with the backup relays. Thus, any electrical fault must be cleared, preferably by the primary relay, and by the backup relay if the primary relay fails to clear the fault. This action allows the remaining healthy system to operate properly as was operating before the fault [1].

Overcurrent protection is predominantly used for the protection of the primary distribution system [2]. Directional overcurrent relays (DOCRs) have been widely reported to be used for protection of interconnected distribution system adequately [3]–[5]. The operating time of a DOCR is obtained from its time-current-characteristic (TCC) curve, as defined by the IEC [6]. For a given fault current, the operating time of a DOCR depends on its two settings parameters: the time multiplier setting (TMS) and pickup current setting (PCS). The protection coordination study's main task is to obtain the suitable values of TMS and PCS of each relay so that minimum CTI between the operating times of all primary-backup relay pairs in the system is always maintained. This task is mostly done through optimum settings of the relays where the problem is formulated as an optimization problem in such a way to minimize the operating times of all the relays subject to maintaining CTI between all primary-backup relay pairs in the system [7]. This problem formulation may be linear programming (LP) or nonlinear programming (NLP) problem. Some types of relays such as electromechanical and static relays require discrete values of the PCS parameter and the continuous value of the TMS parameter. In such situations, this problem becomes a mixed-integer nonlinear programming (MINLP) problem [8]. To solve the optimum protection coordination problem, several analytical and metaheuristic algorithms have been proposed in the literature [9]–[12]. Such protection schemes work well as long as network topology remains fixed.

In practice, change in network topology is frequent because of contingencies due to outages of the transmission lines, transformers, and generating units. The $N-1$ contingency in power networks is very common. In such scenarios, the change in magnitude and direction of faults are likely. These changes may lead to protection coordination issues with DOCRs [13]–[17]. In [14], optimal protection coordination scheme considering change is network topologies was discussed in [13]. Subsequently, this issue was further studied, where the optimal protection coordination scheme of DOCRs has been formulated as an LP problem and solved using the genetic algorithm [14] and interval linear programming [15]. In [16], an adaptive protection coordination scheme has been proposed to tackle dynamically changing topologies and system operating scenarios. Reliable communication is one of the key requirements of this system. For the protection of microgrids considering topological changes has been discussed in [17]. In [18], several aspects of change in network topologies considering tap positions of on-load tap changers have been considered while developing optimum settings of DOCRs.

In most of these studies, all possible $N-1$ contingencies have been considered while calculating the optimum settings of DOCRs. However, in reality, the system's proper operation is not possible under all $N-1$ contingencies because of operating issues [19]. The severity of $N-1$ contingencies can be identified through contingency screening, as mentioned

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in [19]. Those contingencies that do not allow a proper operation of the system are not redundant while planning such a topologies' protection scheme. Therefore, such topologies must not be considered while planning a protection coordination scheme considering $N-1$ contingencies. As a result, the primary-backup relay pairs corresponding to these redundant topologies must be removed while solving the protection coordination problem. This can give a better solution to provide proper protection coordination in the system considering $N-1$ contingencies of interconnected power networks. Therefore, a study is needed in this area to fulfill this gap.

In this paper, the optimal protection coordination scheme of DOCRs consider allowable $N-1$ contingencies is presented. Based on security assessment using a composite security index, all allowable network topologies have been identified. These allowable topologies/configurations are termed as credible contingencies in this work. While developing the optimal settings of DOCRs, all these topologies and their corresponding protection coordination issues of primary-backup relay pairs have been considered. Here, the problem has been formulated as an MINLP problem, and an analytical method based algorithm has been used to solve it. The proposed protection coordination settings' effectiveness and suitability have been demonstrated in the IEEE 14 bus test system.

The rest of this paper is organized as follows. Protection coordination modeling is discussed in Section II. The concept of security assessment based on the composite security index is included in Section III. The overall adopted algorithm and considered parameters are mentioned in Section IV. Simulation results and discussion is given in Section V. Finally. The conclusions are presented in Section VI.

II. Problem Formulation for Protection Coordination

The protection coordination problem of DOCRs is formulated as an optimization problem. In this work, two types of such problem formulations are discussed. The first one is for a single network configuration and the second one is for multiple network configurations. In multiple network configurations, all the credible network configurations created after $N-1$ contingencies are considered. Let us see these two problem formulations one-by-one.

A. For Normal Network Configuration

In this case, protection coordination problem of DOCRs is formulated for a single network topology. The corresponding objective function (OF) can be expressed as,

$$OF = \min\left(\alpha_1 \sum_{i=1}^{m} t_{op,ii} + \alpha_2 \sum_{j=1}^{n} t_{ob,ji}\right) \tag{1}$$

where

$$t_{op,ii} = \frac{0.14 \times TMS_i}{(I_{Fii}/PCS_i)^{0.02} - 1} \tag{2}$$

$$t_{ob,ji} = \frac{0.14 \times TMS_j}{(I_{Fji}/PCS_j)^{0.02} - 1} \tag{3}$$

Subject to

$$t_{ob,ji} - t_{op,ii} \geq MCT \tag{4}$$

$$TMS_{i,min} \leq TMS_i \leq TMS_{i,max} \tag{5}$$

$$PCS_{i,min} \leq PCS_i \leq PCS_{i,max} \tag{6}$$

$$t_{i,min} \leq t_{op,ii} \leq t_{i,max} \tag{7}$$

In (1), $t_{op,ii}$ and $t_{ob,ji}$ are the operating times of primary relay R_i and its corresponding backup relay R_j. Here, m is the total number of relays in the system and n is the total number of primary-backup relay pairs in the system. Also, α_1 and α_2 are non-negative weight factors related to the operating times of primary and backup relays respectively. In (2), I_{Fii} is the fault current passing through relay R_i whereas, TMS_i and PS_i are the settings of relay R_i. Similarly, in (3), I_{Fji} is the fault current passing through backup relay R_j whose primary relay is R_i. Here, (2) and (3) give the TCC of IDMT relay [6].

In the above formulation, (4)-(7) represent the entire set of coordination constraints. A primary backup relay pair is said to coordinate properly when coordination constraint (4) is maintained for any fault in their protection zone. Here, *TMS* and *PCS* for all the relays are the settings parameters of the relays whose optimum values are to be identified within their lower (TMS_{min} and PCS_{min}) and upper (TMS_{max} and PCS_{max}) boundaries. Additionally, the operating times of all the relays must be within their lower (t_{min}) and upper (t_{max}) boundaries.

The lower and upper limits on TMS parameter of the DOCRs are pre-specified by the relays manufacturer. On the other hand, the lower and upper limits on PCS parameter of the DOCRs are to be defined by the protection engineering. Normally, the PCS parameter of DOCRs are specified in terms of the current transformer (CT) secondary rating. Montly, the range of PCS for phase-fault relays are kept within the 0.5–2.0 times CT secondary current rating. Therefore, selection of proper CT rating is also important along with PCS limits. In this work, the range of PCS for DOCRs are defined using the following two equations.

$$PCS_{i,min} = \max\left(0.5, \min\left(1.25\frac{I_{Lmax,i}}{CTR_i}, \frac{I_{fmin,i}}{3CTR_i}\right)\right) \tag{8}$$

$$PCS_{i,max} = \min\left(2, \frac{2I_{fmin,i}}{3CTR_i}\right) \tag{9}$$

where $I_{Lmax,i}$ is the maximum load current and $I_{fmin,i}$ is the minimum fault current passing through relay R_i, whereas, CTR_i is the current transformer ratio (CTR) for relay R_i. These two equations allow the flexibility to set pickup current of the relays between 0.5–2.0 times of CT secondary rating. Additionally, the minimum pickup current setting is kept above the 1.25 times the maximum load current and below the 2/3rd times the minimum fault current seen by CT secondary. These are vary basic requirements while selecting the pickup current setting of DOCRs which is ensure with these equations.

The smaller values of fault current through the relays cause larger operating times of relays. Mostly backup relay of a primary-backup relay pair has sometimes very low fault current. Such types of the pairs can be identified by the condition as follows,

$$I_{fbackup} < \max(2I_{Lmax}, I_{fmin}) \tag{10}$$

The relay pairs whose backup relays satisfy the above conditions are have been ignored. The MCT requirement of such relay pairs will always be maintained because of their higher operating times [18].

This particular formulation is termed as the normal network configuration (NNC) case.

B. For Contingency Network Configuration

In this case, protection coordination problem of DOCRs is formulated for which can coordinate properly under credible $N-1$ contingency. The objective function considering contingency (OFC) are expressed as,

$$\mathit{OFC} = \min \sum_{l=1}^{nc} \left(\alpha_1 \sum_{i=1}^{m} t_{op,iil} + \alpha_2 \sum_{j=1}^{n} t_{ob,jil} \right) \tag{11}$$

where

$$t_{op,iil} = \frac{0.14 \times \mathit{TMS}_i}{(I_{Fiil}/\mathit{PCS}_i)^{0.02} - 1} \tag{12}$$

$$t_{ob,jil} = \frac{0.14 \times \mathit{TMS}_j}{(I_{Fjil}/\mathit{PCS}_j)^{0.02} - 1} \tag{13}$$

Subject to

$$t_{ob,jil} - t_{op,iil} \geq \mathit{MCT} \tag{14}$$

$$t_{i,min} \leq t_{op,iil} \leq t_{i,max} \tag{15}$$

$$(5) - (6) \tag{16}$$

In (11), nc is the total number of $N-1$ contingencies under which the system under study is running successfully. In (12), I_{Fiil} denotes the fault current through relay R_i in l^{th} configuration and $t_{op,iil}$ is the operating time of relay R_i in l^{th} configuration. Similarly, in (13) I_{Fjil} denotes the fault current through backup relay R_j whose primary relay is R_i in l^{th} configuration and $t_{op,jil}$ is the operating time of the backup relay R_j in l^{th} configuration. Here, (14) ensures that all the coordination constraints are satisfied in the obtained solution.

This particular formulation is termed as the contingency network configuration (CNC) case.

C. Calculation of Current Transformer Ratio

For calculating the CT ratio of i^{th} relay, following procedure has been adopted. Let there be a total of N credible configurations in a system. Corresponding to any k^{th} configuration ($1 \leq k \leq N$), the load current passing through the relay ($i_{Lk,i}$) and the fault current passing through the relay ($i_{fk,i}$) is calculated. Subsequently, $i_{LmaxA,i}$ and $i_{fmaxA,i}$ is calculated as; $i_{LmaxA,i} = max(i_{L1,i}, i_{L2,i}, ..., i_{LN,i})$ and $i_{fmaxA,i} = max(i_{f1,i}, i_{f2,i}, ..., i_{fN,i})$. Finally, the primary side rating of the CT corresponding to relay R_i is calculated as [1],

$$\mathit{CTR}_i = \max\left(I_{LmaxA,i}, \frac{I_{fmaxA,i}}{20}\right) \tag{17}$$

Once CTR_i is calculated, the CT of CTR_i:1 is used.

D. Load and Fault Currents Calculations

In this study, the following have been considered to calculate various current.

1) I_{Lmax}: Newton-Raphson load flow method
2) I_{fmax}: Bolted three-phase using Z_{bus} method
3) I_{fmin}: Phase-phase fault using Z_{bus} method

In this study, the faults have been applied in the middle of each line.

Now, in any system, the number of possible $N-1$ contingencies can be quite high. However, only the credible contingencies (out of all possible contingencies) need to be considered for protection coordination. For selecting the credible contingencies, the composite security index has been followed in this work, as discussed in the next section.

III. Composite Security Index

The composite security index (CSI) provides an efficient method for contingency selection and ranking. It is defined in terms of the limit violations of bus voltages and line power flows. Two types of limits are defined for bus voltages, and line power flows: "alarm limit" and "security limit". The alarm limit indicates a closeness to limit violations. The security limit is the maximum limit specified for the bus voltages and line power flows. In this study, alarm and security limits on the bus voltages have been taken as ±5% and ±7% variation from the desired value (1.0 p.u.) respectively, whereas 80% of the specified thermal limit of line power flow has been taken as the alarm limit of the line power flow [20].

The CSI selects only credible cases and ranks them in the order of severity. The CSI has two components: a) bus voltage security index and b) line power flow security index. These components and the CSI, as suggested in [19], [20], have been adopted in this work and are discussed below.

The normalized lower and upper voltage limit violations beyond the alarm limits are expressed as,

$$\begin{aligned} r^l_{v,ib} &= \frac{[V^{la}_{ib} - V_{ib}]}{[V^{la}_{ib} - V^{ls}_{ib}]} && ;if\ V_{ib} < V^{la}_{ib} \\ r^l_{v,ib} &= 0 && ;if\ V_{ib} \geq V^{la}_{ib} \\ r^u_{v,ib} &= \frac{[V_{ib} - V^{ua}_{ib}]}{[V^{us}_{ib} - V^{ua}_{ib}]} && ;if\ V_{ib} > V^{ua}_{ib} \\ r^u_{v,ib} &= 0 && ;if\ V_{ib} \leq V^{ua}_{ib} \end{aligned} \tag{18}$$

In (18), V^{la}_{ib}, V^{ua}_{ib}, V^{ls}_{ib} and V^{us}_{ib} represent the lower and the upper alarm and security limits of voltages of bus *ib* respectively. By using (18), bus voltage security index (BVSI) can be defined as,

$$\mathit{BVSI} = \left[\sum_{ib} \left(r^l_{v,ib}\right)^2 + \sum_{ib} \left(r^u_{v,ib}\right)^2 \right]^{1/2} \tag{19}$$

For line power flow, only the maximum power flow limits of each line are required to be specified. The normalized upper line power flow limit violations beyond the alarm limits are expressed as,

$$\begin{aligned} r^u_{p,jk} &= \frac{[|P_{jk}| - P^{ua}_{jk}]}{[P^{us}_{jk} - P^{ua}_{jk}]} && ;if\ P_{jk} > P^{ua}_{jk} \\ r^u_{p,jk} &= 0 && ;if\ P_{jk} \leq P^{ua}_{jk} \end{aligned} \tag{20}$$

In (20), P_{jk}^{ua} and P_{jk}^{us} represent the alarm and the security limits of each line *jk*. By using (20) line power flow security index (LPFSI) can be defined as,

$$LPFSI = \Big[\sum_{jk} \left(r_{p,jk}^{u}\right)^{2}\Big]^{1/2} \tag{21}$$

Using (19) and (21) the composite security index (CSI) is defined as,

$$CSI = \Big[BVSI^{2} + LPFSI^{2}\Big]^{1/2} \tag{22}$$

Depending on the value of CSI from (22), the following conclusions can be drawn about the state of the system,

a) insecure state if $CSI > 1$

b) alarm state if $0 < CSI \leq 1$

c) secure if $CSI = 0$.

In this work, the composite security index defined by (22) has been considered for contingency ranking.

IV. Adopted Optimization Algorithm

To solve the protection coordination problem of DOCRs formulated as an MINLP type, a two-phase interior-point method (IPM) based algorithm has been introduced in [18]. In the phase-I of this algorithm, the DOCRs problem is considered an NLP problem and solved using IPM. Subsequently, the lower and upper limits of all the discrete variables are redefined to the nearest discrete values of the obtained solution of phase-I, and some additional variables and constraints included in the problem. After that, IPM is again applied, which gives the optimum values of all discrete variables along with the optimum values of all the continuous variables.

The TMS and PCS parameters of DOCRs can have any continuous values within their ranges for numerical/digital type relays. TMS can have any continuous value, and PCS can only have certain fixed discrete values for static or electromechanical type relays within their respective ranges [21]. Consequently, the optimum coordination problem of DOCRs can be termed as an NLP problem if all the relays considered in the system are of numerical/digital type. If static or electromechanical relays are also considered and the numerical/digital relays, then the optimum relay coordination problem can be termed as an MINLP problem.

In this work, all the relays are considered to have continuous TMS and discrete PCS parameters. As a result, the problem is termed as MINLP problem, which is solved using the IPM based algorithm discussed in [18] has been adopted. The range of TMS is considered within [0.1, 1.1] and the range of PCS is considered according to (8) and (9). The discrete step of PCS is assumed as 0.25 within the lower to the upper limits. The value of MCT considered in this study is 0.3 seconds [21]. Also, range of t_{op} has been considered within [0.1, 4.0] sec.

The proposed strategy has been simulated in the AMPL environment [22]. It is to be noted that while simulating the outage of a generator, the generation levels of the remaining generators are increased proportionately to their MVA ratings to compensate for the lost generation.

V. Simulation Results and Discussion

The proposed approach has been validated on the IEEE 14-bus test system. This test system is having 20 lines and is supplied by 5 generating sources [23]. Out of these 5 generating sources, 2 are generators while the remaining 3 are synchronous condensers. To protect this system using DOCRs, a total of 40 DOCRs (two DOCRs for each line) need to be used and coordinated with each other.

1) Normal network configuration (NNC)
2) $N-1$ contingency network configuration (CNC)

In the NNC case, all the DOCRs are expected to coordinate properly for that particular network configuration. In CNC scenario, the DOCRs are expected to coordinate properly for all credible $N-1$ contingency network configurations (i.e. with *CSI* <1). In this case, initially, the ranking of all $N-1$ contingencies is carried out based on the values of CSI (discussed in Section III). Subsequently, all the network configurations with *CSI* <1 are considered feasible, which are to be protected using DOCRs. After that, the steady-state currents and various fault currents are calculated for all these feasible configurations. The details of these calculations are not included in the paper for brevity.

A. Simulation Results

Fig. 1 shows the single-line diagram of IEEE the 14-bus system having 40 DOCRs placed on 20 lines (two on each line). There are 93 primary-backup relay pairs, which are given in Table I.

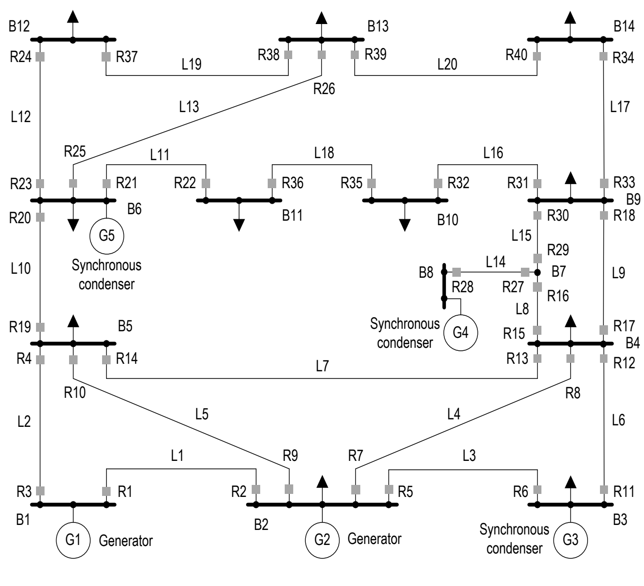

Fig. 1. IEEE 14-bus system.

1) Normal network configuration (NNC): In this case, there are a total of 93 primary-backup relays pairs among all the 40 relays, as given in Table I. It is to be noted that only 70 relay pairs have been considered in the optimization as the other 23 relay pairs are satisfying eqn. (10) in which coordination constraints always remain satisfied.

2) $N-1$ contingency network configuration (CNC): In this system, there are 20 lines and 5 generators, i.e., 25 elements that can experience contingency. Therefore, under

TABLE I

PRIMARY/BACKUP RELAY PAIRS FOR THE STANDARD IEEE 14-BUS SYSTEM

Faulty line	Pair No.	Primary relay	Backup relay	Faulty line	Pair No.	Primary relay	Backup relay
L1	1	1	4	L9	48	17	28
	2	2	6		49	17	30
	3	2	8		50	18	15
	4	2	10		51	18	28
L2	5	3	2		52	18	32
	6	4	9		53	18	34
	7	4	13	L10	54	19	3
	8	4	20		55	19	9
L3	9	5	1		56	19	13
	10	5	8		57	20	22
	11	5	10		58	20	24
	12	6	12		59	20	26
L4	13	7	1	L11	60	21	19
	14	7	6		61	21	24
	15	7	10		62	21	26
	16	8	11		63	22	35
	17	8	14	L12	64	23	19
	18	8	18		65	23	22
	19	8	28		66	23	26
	20	8	30		67	24	38
L5	21	9	1	L13	68	25	19
	22	9	6		69	25	22
	23	9	8		70	25	24
	24	10	3		71	26	37
	25	10	13		72	26	40
	26	10	20	L15	73	30	17
L6	27	11	5		74	30	32
	28	12	7		75	30	34
	29	12	14	L16	76	31	15
	30	12	18		77	31	17
	31	12	28		78	31	28
	32	12	30		79	31	34
L7	33	13	7		80	32	36
	34	13	11	L17	81	33	15
	35	13	18		82	33	17
	36	13	28		83	33	28
	37	13	30		84	33	32
	38	14	3		85	34	39
	39	14	9	L18	86	35	31
	40	14	20		87	36	21
L8	41	15	7	L19	88	37	23
	42	15	11		89	38	25
	43	15	14		90	38	40
	44	15	18	L20	91	39	25
L9	45	17	7		92	39	37
	46	17	11		93	40	33
	47	17	14		-	-	-

the CNC scenario, there are a total of 25 configurations generated by $N-1$ contingencies. Out of these 25 contingencies, 23 contingencies have $CSI < 1$, and therefore, these configurations are considered feasible system topologies. Therefore, for deciding the relays' parameters, a total of 24 configurations (23 contingency configurations and one normal configuration) are considered. As each configuration has 93 primary-backup relay pairs, the total number of primary-backup relay pairs considered under contingency is 2332 (24×93). It is to be noted that only 1167 relay pairs out of 2332 have been considered in the optimization in this scenario, as the remaining 1165 relay pairs satisfy eqn. (10) thereby ensuring that the coordination constraints are always satisfied for these relay pairs.

The optimum settings of the relays obtained in both the cases (NNC and CNC) are given in Table II. Further, the optimized CTI between the operating times of primary and backup relay pairs are shown in Fig. 2 and Fig. 3 respectively, in both cases. From these figures, it is observed that the minimum CTI is always maintained for any primary-backup relay pair, thereby ensuring the selectivity of the relays.

TABLE II

OPTIMUM SETTING OF THE RELAYS

Relays	NNC		CNC	
	TMS	PS	TMS	PS
1	0.1	0.75	0.1139	1
2	0.1	0.5	0.2059	2
3	0.1017	1.25	0.1	1.5
4	0.1	0.5	0.1	0.5
5	0.1	1.25	0.1162	1.25
6	0.1	1.25	0.5365	0.5
7	0.1287	1	0.152	1
8	0.1034	1	0.2999	1
9	0.1596	1	0.1296	1.25
10	0.1	1	0.2109	1.5
11	0.2648	0.5	0.4616	0.5
12	0.1	2	0.1	0.75
13	0.1	2	0.1785	1.5
14	0.1089	1	0.1068	1
15	0.105	1.75	0.135	1.25
16	0.1	0.5	0.1	0.5
17	0.1258	2	0.12	1.75
18	0.1	1.5	0.1917	1
19	0.104	1.5	0.1377	1.25
20	0.1	0.5	0.3208	0.5
21	0.2334	2	0.2895	2
22	0.1935	2	0.1416	2
23	0.1547	2	0.2763	2
24	0.3274	0.5	0.366	0.75
25	0.1914	2	0.2121	1.75
26	0.1316	2	0.2873	1.25
27	0.1	1.25	0.1	1
28	0.4535	0.5	0.5977	0.5
29	0.1	1	0.1	0.5
30	0.1361	2	0.149	2
31	0.2489	2	0.2509	1.25
32	0.3466	0.5	0.3427	1
33	0.1795	2	0.1395	2
34	0.227	2	0.3849	1.75
35	0.2215	2	0.148	2
36	0.2513	2	0.2571	2
37	0.1393	2	0.4136	1.25
38	0.1654	2	0.1662	2
39	0.2051	2	0.206	2
40	0.175	2	0.2033	2
$\sum_{i=1}^{40} t_{op,i}$	17.9778		26.5592	

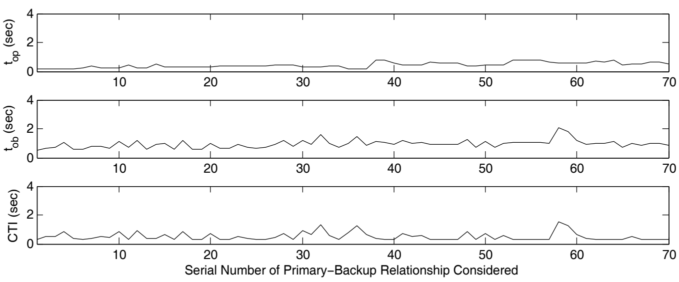

Fig. 2. Optimized CTI in NNC case.

B. *Effectiveness of the Settings under* $N-1$ *Contingencies*

To test the effectiveness and the robustness of the considered method for both NNC and CNC scenarios, a statistical analysis has been performed by running the considered method 100 times independently with different initial solutions. Table III shows the statistical summary of the results.

TABLE III

STATISTICAL RESULTS OBTAINED AFTER 100 RUNS

Methods	Sum of operating times of all relays			Standard deviation	Mean solution time per run (sec)
	Best	Mean	Worst		
NNC	17.9778	17.9778	17.9778	0	0.2505
CNC	26.5592	26.5592	26.5592	0	0.6294

Table II, it is observed that the sum of the operating times of all the relays in the NNC scenario is 17.9778 seconds,

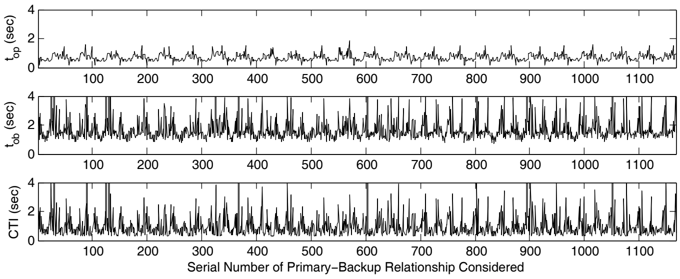

Fig. 3. Optimized CTI in CNC case.

whereas the sum of the operating times of all the relays in the CNC scenario is 26.5592 seconds. Subsequently, from Table II and Table III, it is observed that the sum of the operating times of all the 40 relays is more for CNC than those for NNC. This is because the relay settings obtained for CNC can maintain protection coordination under all the credible $N-1$ contingencies of the system. In other words, a relatively higher value of the sum of operating times for the CNC case is because of the robustness of the settings to provide proper coordination to the network under the credible $N-1$ contingencies of the system. Further, zero standard deviation by the considered method in both the cases indicates the reproducibility of the results even when each run starts from different initial conditions. Also, a small mean simulation time indicates the method's effectiveness in solving this complex optimization problem. Further, from Fig. 2 and Fig. 3, it is observed that the MCT requirement of 0.3 seconds is always maintained in both NNC and CNC scenarios of the system. Therefore, the settings obtained under the CNC scenario can maintain the relay coordination properly under all the system's credible configurations.

Therefore, the robust protection coordination settings of DOCRs are obtained in CNC scenarios in which the settings of the relays can coordinate properly under all credible contingency cases of the system. These settings of DOCRs are to be considered for the protection of the system.

VI. Conclusion

This paper proposes optimum settings of directional overcurrent relays considering network security assessment. In this study, a single setting of the relays has been presented to provide proper coordination among the relays under all allowable $N-1$ contingencies. All allowable contingencies have been identified using a composite security index through a static security assessment. The presented scheme's feasibility has been analyzed, which proves its effectiveness in providing robust settings under changing network topology caused by $N-1$ contingencies. The obtained setting can provide proper coordination during allowable $N-1$ contingencies of the system. In a further study, protection coordination of DOCRs considering setting groups will be presented for power network running under changing system topology caused by contingencies. Additionally, the impact of the integration of distributed generation will be considered in the protection coordination studies.

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