International Journal of Electrical and Computer Engineering (IJECE)
Vol. 10, No. 1, February 2020, pp. 72~79
ISSN: 2088-8708, DOI: 10.11591/ijece.v10i1.pp72-79

Inter-trip links incorporated optimal protection coordination

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Article Info

Article history:

Received Mar 23, 2019
Revised Aug 13, 2019
Accepted Aug 29, 2019

Keywords:

Distribution network
Genetic algorithm
Inter-trip link
OverCurrent relays
Protection coordination

ABSTRACT

Due to advances in smart grid, different communication links as delay, inter-trip and activation are used between relays to enhance the protection system performance. In this paper, the effect of inter-trip links on optimal coordination of directional overcurrent relays (DOCRs) is analytically investigated and modelled. Moreover, an index is proposed to find the optimum locations for inter-trip link installation to reach the minimal fault clearance times under the selectivity constraint. Then a method is proposed to determine the candidate locations of inter-trip links and the associated reduced operating times. An Exhaustive search approach is also used to validate the efficiency of the proposed method. The method is simulated and tested on distribution network of IEEE 33 bus using the Power Factory software and MATLAB optimization toolbox. Genetic algorithm is used as an optimization tool to find optimal settings of relays. The results indicate the capability of proposed method in optimal protection coordination with optimum inter-trips.

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1. INTRODUCTION

Protection coordination tries to design a sensitive protection under the selectivity constraint. Optimal coordination of DOCRs can be formulated as an optimization problem. Several deterministic and heuristic methods such as simplex, particle swarm optimization, genetic algorithm and harmony search algorithm are proposed in the literature to find the optimum relay settings [1-6].

Nowadays and due to advances in communication infrastructures related to smart grid, communication-assisted protection scheme has been received attention to be applied in distribution networks. In communication-assisted protection systems, different links as delay, block, inter-trip and differential scheme are used to improve the DOCRs performance. Differential protection is also reviewed attention due to low fault current contribution of inverter-based distributed generation.

Differential protection is generally used for microgrid protection due to low short circuit currents in islanded mode of operation [7-11]. Different communication tools as power line carrier [9] and fiber optics are used. In [12-14] differential protection is used for distribution network protection to cope with different short circuit levels. In [12] hybrid differential adaptive protection is used for where in case of communication failure, the differential relays changes their role to adaptive overcurrent ones. Multi-layer differential scheme is also proposed to provide the backup protection [13-15].

Adaptive protection where the data is exchanged from a central unit to the DOCRs in non-fault condition is becoming popular due to uncertainties in distribution grids. In adaptive protection, due to changes in grid structure or connection status of distribution generation, the new settings of relays are calculated offline [16-18] or online [19-21] and then transmitted to the relays.

Data exchange between relays during the faulted period can be performed as inter-trip, delay and block. In [22] simple definite time relays with delay and block signals on GOOSE bed is used for islanded distribution grid. Similar idea with two definite time settings along with delay and inter-trip is used in [23]. In [24] delay signals is used for fault clearance time reduction and stable operation of low inertia distributed generations. Bidirectional relays with block signals are introduced in [25] where all relays are communicating during the fault for both sensitivity and selectivity. This work is completed in [24] as only the candidate relays act bidirectional to minimize the required data network.

As the authors' knowledge, the relays optimal coordination problem is not investigated in presence of inter-trip links. Inter-trip links are used to achieve to fast fault clearance on the applied protective zone, indirectly affecting the other relays operation times. In this paper, concept of inter-trip incorporated protection coordination is introduced and the required formula is developed. Moreover, inter-trip impact on protection coordination is investigated and modeled. Finally, a new method based on introduced index is proposed to find the optimum locations for inter-trip installation with the goal of reduction in fault clearance time. The paper is organized as follows. The next section describes the conventional protection coordination. Inter-trip modeling and the proposed method are explained in section 3. Section 4 represents the simulation results for different scenarios.

2. OPTIMAL PROTECTION COORDINATION

The optimal protection coordination can be formulated as an optimization problem with an objective function stated in (1).

$$Min\ T = \sum_{f=1}^{f_n} \sum_{i=1}^{n} t_{i,f_i} \tag{1}$$

Where f indicates the near-end and far-end faults, i represents primary relay indices and t_{i,f_i} is the operating time of primary relay i for a near/far end fault f_i.

To ensure the selectivity of the protection system, the operating time of backup relay should lag enough, as Coordination Time Interval (CTI). The coordination constraint is shown in (2). The typical value of CTI lies in range of 200-300 ms. j is the backup relay indices and t_j is the operating time of backup relay.

$$t_j - t_i \geq CTI\ for\ all\ f_i \tag{2}$$

The operating time of DOCR is given by (3) as follows

$$t = \frac{A}{(\frac{I_f}{I_p})^B - 1} TDS \tag{3}$$

Where I_f is the fault current seen by the relay, TDS is relay Time Dial Setting (TDS) and I_p is the relay pick up current. Constants$A$ and B define the relay curve type. The relay I_p and TDS are bounded as below.

$$\begin{gathered} TDS_{min} \leq\ TDS\ \leq TDS_{max} \\ I_{pmin} \leq\ I_p\ \leq I_{pmax} \end{gathered} \tag{4}$$

3. INTER-TRIP INCORPORATED PROTECTION COORDINATION

Inter-Trip link is used between relays at both ends of a line where relays are communicating with each other through the link. The link can be in form of power line carrier, pilot wires and optical fibers. A simple inter-trip link between the relays is shown in Figure 1, where relays R_a and R_b are exchanging data through the dedicated link.

The main goal of using inter-trip links is to reduce the fault clearance time. Operation principle of inter-trip link can be explained as follows. Once a fault like F_1 occurs in the main protection zone of relays R_a and R_b, they pick up the fault current. When the relays picked up for duration, they send each other the pickup activation signal. Since the no synchronous data measurement and transmission is required and low data rate is transferred, the inter-trip link requirements are not as strict as differential protection and which results in lower cost.

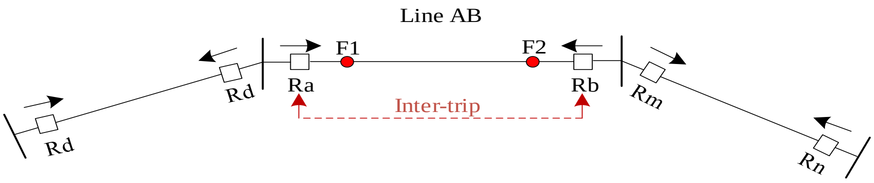


Figure 1. Inter-trip example

The relays R_a and R_b issue a trip if they pick up the local current and receive a pickup activation signal from the other end relay. The inter-trip is used for quick fault isolation in the relevant line where the operating time associated with relay setting is high. Assuming a minimum pickup duration of T_{pickup} and the latency and process time as t_{delay}, the trip signal for fault F1 by inter-trip module is as (5).

$$t_{inter-trip} = T_{pickup} + t_{delay} \tag{5}$$

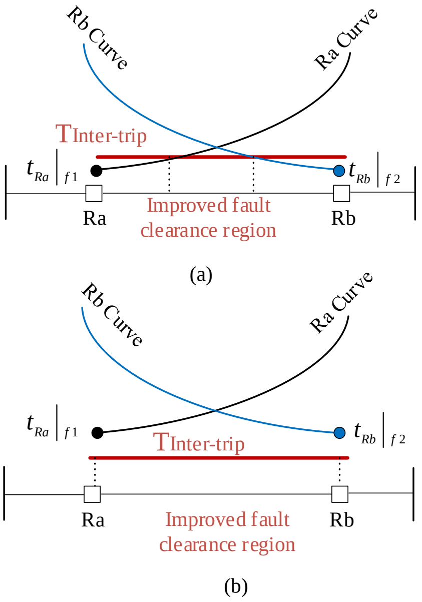
The relay tripping time for faults in primary zone as F_1 and F_2 incorporating the inter-trip module can be formulated as (6).

$$\begin{aligned} t^*_{Ra} &= \min(t_{Ra}, t_{inter-trip}) \\ t^*_{Rb} &= \min(t_{Rb}, t_{inter-trip}) \end{aligned} \tag{6}$$

where t_{Ra} and t_{Rb} are the tripping time issued by settings and t^*_{Ra} and t^*_{Rb} are the overall tripping time of relays considering the inter-trip module. As seen form (6), the overall effect of inter-trip is to decrease the fault clearance time in the relevant line. The effect of inter-trip is dependent on the settings of R_a and R_b which is obtained through optimal protection coordination. The inter-trip link has two direct and indirect impacts on protection coordination problem which is described as below.

In a meshed grid, it can be assumed that each relay trips the near end fault faster than other relay, which is a realistic assumption. The relay tripping time based on settings can be shown based on as Figure 2(a). The incorporated inter-trip link is illustrated with a constant tripping time for all faults in line AB which is shown by a solid red line. As seen, the inter-trip decreases the fault clearance time in some sections of line AB. The full potential of inter-trip is employed if the $t_{Ra}|_{f1}$ and $t_{Rb}|_{f2}$ are allocated above the inter-trip line as shown in Figure 2(b). This can be formulated as the necessity condition for inter-trip installation as indicated in (7).

$$t_{inter-trip} \leq \min(t_{Ra}|_{f1}, t_{Rb}|_{f2}) \tag{7}$$



(a)

(b)

Figure 2. Direct impact of inter-trip link

The above mentioned situation expresses the condition for maximum utilization of inter-trip direct impact. As a direct impact, the inter-trip lowers the fault clearance time in line AB to the $t_{inter-trip}$. The indirect impact of the inter-trip can be investigated though the Figure 3 where tripping curves of R_a and its backup R_c are plotted. Due to the inter-trip signal, the tripping curve of R_a is modified which is similar to a definite time curve. Due to increased time difference between $R_a$and R_c, the setting of R_c can be modified to achieve more sensitive operation which is also shown. The new settings of R_c should satisfy two coordination constraints as below.

As seen, the relay R_c settings become more sensitive with applying the inter-trip on line AB and this phenomena can be generalized to all upstream relays. This is the indirect impact of inter-trip utilization, which results in the operating time reduction of other relays. The new settings of R_c should satisfy following constraints considering inter-trip link between R_a and R_b

$$\begin{aligned} & t^*_{Rc}|_{f2} - t_{Ra}|_{f2} \geq CTI \\ & t^*_{Rc}|_{f1} - \min(t_{Ra}|_{f1}, t_{inter-trip}) \geq CTI \end{aligned} \tag{8}$$

Summarizing the mentioned formulas, an index can be used for optimum allocation of inter-trip links to reduce the overall operating times of relays. The proposed index is given in (9) which should be calculated for each line.

$$Index = \alpha \times DI + \beta \times IDI \tag{9}$$

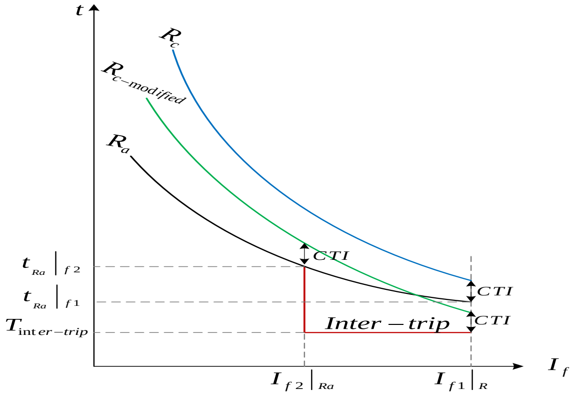


Figure 3. Indirect impact of inter-trip link

where DI and IDI are the direct and indirect impact components of inter-trip installation at a given location. α and β are the weighting factors. The DI for line AB in Figure 1 can be calculated as in (10).

$$\begin{aligned} & DI_{F1} = t_{Ra}|_{f1} - \min\left(t_{Ra}|_{f1}, t_{inter-trip}\right) + t_{Rb}|_{f1} - \min\left(t_{Rb}|_{f1}, t_{inter-trip}\right) \\ & DI_{F2} = t_{Ra}|_{f2} - \min(t_{Ra}|_{f2}, t_{inter-trip}) + t_{Rb}|_{f2} - \min(t_{Rb}|_{f2}, t_{inter-trip}) \end{aligned} \tag{10}$$

$$DI = DI_{F1} + DI_{F2}$$

The IDI reflects the sensitivity increase in neighbor relays i.e. backup relays of R_d and R_n, where it can be calculated considering the (7) and Figure 1. IDI should be calculated for each relay as shown in (11).

$$IDI = \gamma \times \sum_{n=1}^{N_b} (t_{backup}\big|_{far} - t_{primary}\big|_{far}) \tag{11}$$

where γ is a binary coefficient to exclude backup relays with no operating time reduction and N_b is total number of backup relays. Two conditions should be reached for IDI being nonzero. First, the relevant DI term should be nonzero and the coordination constraint should be a binding constraint. In case of zero DI of primary relay for near end fault, the backup relay cannot become more sensitive as shown in Figure 3. Moreover, in case of non-binding constraint, the setting of the backup relay is dictated with other relays not the relays with inter-trip. γ is described as (12).

$$\gamma = \begin{cases} 0 & non-binding\ constraint \\ 0 & t_{primary}\big|_{near} - t_{inter-trip} \leq 0 \\ 1 & else \end{cases} \qquad (12)$$

The proposed method for optimal inter-trip allocation is depicted in Figure 4. At initial step, optimal coordination of relays is performed. Then the proposed index is calculated for all lines. The inter-trip is modeled and the best location is selected according to the propose index. Then protection coordination is run again to re-calculate the index for next inter-trip location. This process continues until the all locations for the known number of inter-trips are found.

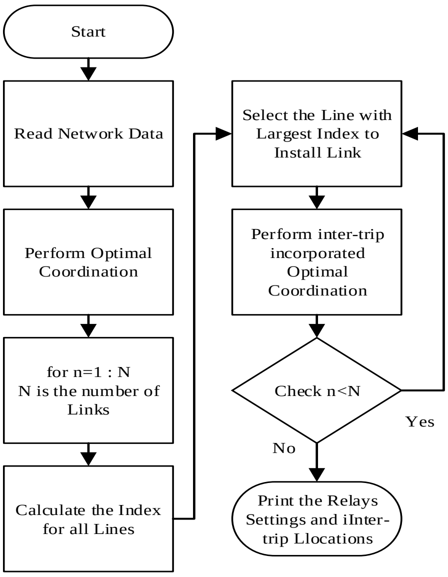


Figure 4. Flowchart of proposed algorithm

4. SIMULATION RESULTS AND DISCUSSIONS

The proposed method for optimum inter-trip link allocation with optimal protection coordination is tested on modified IEEE 30 bus network. IEEE 30 bus is composed of sub-transmission and distribution networks where the distribution part is studied here which is shown in Figure 5. Three DGs are added to form an active distribution network. As seen, 43 DOCRs are used to isolate the faults and very inverse curve is assumed for all DOCRs. Different scenarios are simulated to present the capability of the proposed method. Genetic algorithm is used as an optimization tool for optimal protection coordination.

Scenario A, no inter-trip link: In this scenario, no inter-trip link is used and the conventional protection coordination is performed for the case study grid. The genetic algorithm convergence during the optimization process is shown in Figure 6. The total operating time is 31.6958 s and the optimal settings of relays are listed in Table 1.

Scenario B, single inter-trip link: In this scenario, exhaustive search and the proposed index are used to determine the best location for single inter-trip location. The proposed index is calculated using the previous settings to find best location for the inter-trips. Table 2 lists the five most appropriate candidates for inter-trip location calculated by proposed method and the exhaustive search. As seen the line R25R26 is the best candidate location to install the inter-trip. The results of exhaustive validates the capability of proposed method where same priority list is found by both proposed and exhaustive search method. The optimal settings of relays with an inter-trip link installed on R25R26 are listed in Table 3. There is about 2.5 s reduction in total operating time of relays. As seen, the neighbor relays settings became more sensitive. For example the R28 pickup current is decreased from 0.342 to 0.2743 and the TDS is remained constant.

Scenario C, three inter-trip link installations: In this scenario, the proposed method in flowchart is run to find the optimum locations of three inter-trip links. The proposed method assigned the links to the R25R26, R7R8 and R13R14. Protection coordination considering the installed inter-trips are performed where the obtained optimal settings of relays is reported in Table 4. Total operating time is decreased from 31.56 to 25.57 s due to installed three inter-trip links. Table 5 represents relays operating times for some near-end faults based on settings obtained in scenario C.

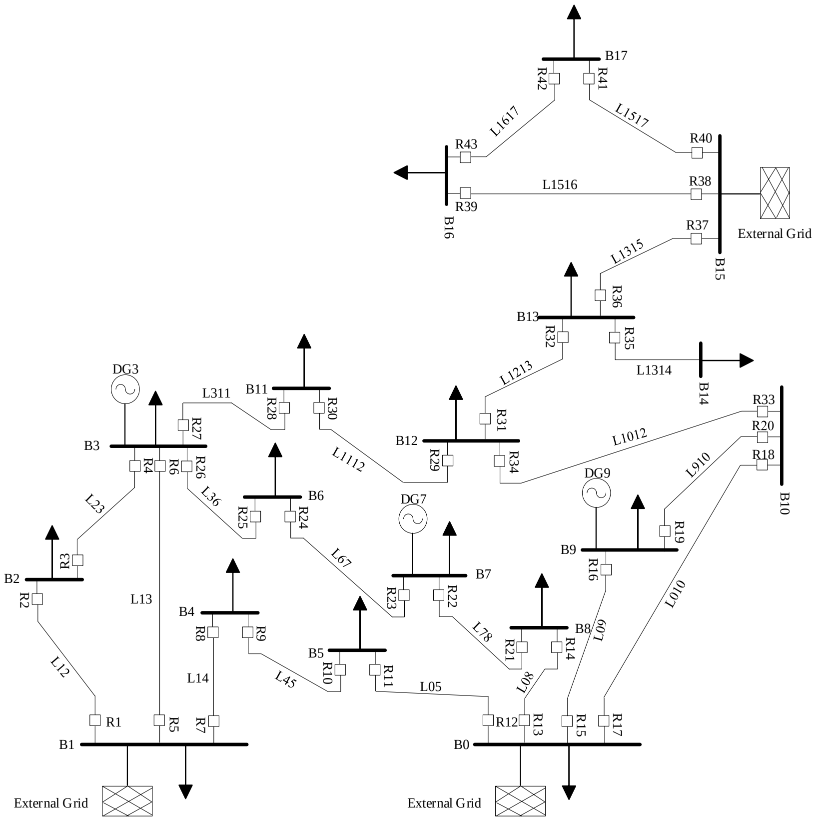


Figure 5. Case study network

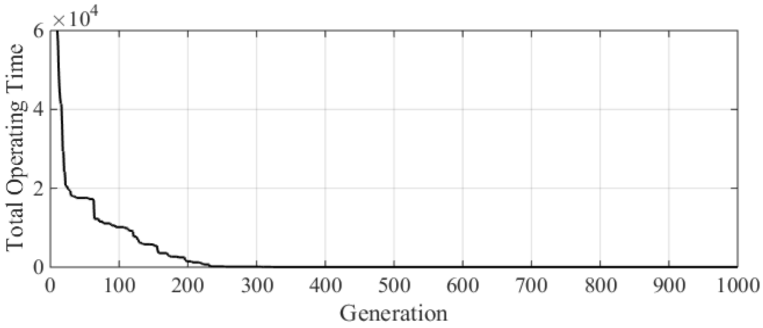


Figure 6. Convergence of genetic algorithm for scenario A

Table 1. Optimal setting of relayes for scenario A

Relay No.	Ip(pu)	TDS	Relay No.	Ip(pu)	TDS	Relay No.	Ip(pu)	TDS
R1	0.2223	0.3494	R16	0.208	0.2608	R31	0.5117	0.1101
R2	0.1132	0.1298	R17	0.123	0.6547	R32	0.305	0.1957
R3	0.0652	0.5435	R18	0.1034	0.4023	R33	0.2893	0.3223
R4	0.0894	0.5991	R19	0.1458	0.8247	R34	0.3044	0.2889
R5	0.4251	0.3128	R20	0.1486	0.6248	R35	0.0991	0.0528
R6	0.3058	0.2048	R21	0.1933	0.7909	R36	0.3802	0.0812
R7	0.2925	0.5876	R22	0.1261	0.9105	R37	0.3878	0.2346
R8	0.4342	0.0878	R23	0.2049	0.7138	R38	0.1706	0.2158
R9	0.2101	0.5722	R24	0.2865	0.3774	R39	0.1601	0.05
R10	0.2128	0.3909	R25	0.184	0.5945	R40	0.2734	0.1632
R11	0.3108	0.2683	R26	0.171	0.9306	R41	0.1381	0.0501
R12	0.3406	0.468	R27	0.1599	0.7636	R42	0.1265	0.1693
R13	0.2116	0.9597	R28	0.342	0.1175	R43	0.0817	0.2303
R14	0.1631	0.457	R29	0.1521	0.5047	Total Operating Time		31.6958
R15	0.3106	0.4954	R30	0.2402	0.2913			

Table 2. Five most appropriate candidates for inter-trip location

Proposed Method		Exhaustive search	
Line	Index value	Inter-trip location	Operating time obtained by GA.
R25R26	2.84976	R25R26	28.9694
R13R14	2.31074	R13R14	29.5619
R23R24	1.94092	R23R24	29.5905
R21R22	1.85686	R21R22	29.8624
R9R10	1.23856	R9R10	30.3784

Table 3. Optimal settings of relayes for scenario B: inter-trip on line R25R26

Relay No.	Ip(pu)	TDS	Relay No.	Ip(pu)	TDS	Relay No.	Ip(pu)	TDS
R1	0.1599	0.4619	R16	0.3272	0.149	R31	0.3984	0.1505
R2	0.119	0.1216	R17	0.1199	0.6575	R32	0.3028	0.1985
R3	0.089	0.3328	R18	0.1081	0.3792	R33	0.1692	0.5395
R4	0.0767	0.6989	R19	0.1513	0.7775	R34	0.22	0.4206
R5	0.1904	0.659	R20	0.1694	0.5262	R35	0.094	0.0502
R6	0.3803	0.1577	R21	0.2083	0.7089	R36	0.3621	0.0868
R7	0.3613	0.4705	R22	0.1938	0.571	R37	0.4093	0.2211
R8	0.3495	0.1116	R23	0.1451	0.984	R38	0.1572	0.2238
R9	0.1548	0.7956	R24	0.2496	0.4356	R39	0.1575	0.0501
R10	0.1269	0.6723	R25	0.2022	0.5688	R40	0.2088	0.219
R11	0.2524	0.3395	R26	0.2066	0.8666	R41	0.1385	0.05
R12	0.2229	0.7346	R27	0.2121	0.5794	R42	0.1648	0.1236
R13	0.2202	0.8993	R28	0.2743	0.1207	R43	0.1462	0.1088
R14	0.1816	0.4009	R29	0.1384	0.4932	Total Operating Time		28.9694
R15	0.4045	0.3666	R30	0.1725	0.4291			

Table 4. Optimal settings of relayes for scenario C: three inter-trip links

Relay No.	Ip(pu)	TDS	Relay No.	Ip(pu)	TDS	Relay No.	Ip(pu)	TDS
R1	0.1599	0.464	R16	0.2388	0.1925	R31	0.3179	0.1963
R2	0.1778	0.0567	R17	0.1185	0.6513	R32	0.2832	0.2159
R3	0.0739	0.4071	R18	0.1238	0.3219	R33	0.2519	0.3456
R4	0.1236	0.3923	R19	0.146	0.7937	R34	0.1889	0.4966
R5	0.4194	0.2724	R20	0.2044	0.4163	R35	0.0937	0.0501
R6	0.3051	0.1558	R21	0.1565	0.9462	R36	0.3627	0.0867
R7	0.3452	0.7328	R22	0.2104	0.451	R37	0.4313	0.2089
R8	0.4311	0.1044	R23	0.1704	0.8147	R38	0.1938	0.1786
R9	0.2212	0.5319	R24	0.1421	0.7246	R39	0.1572	0.05
R10	0.2196	0.3381	R25	0.1367	0.8711	R40	0.2186	0.2095
R11	0.35	0.2286	R26	0.1945	0.8419	R41	0.1381	0.05
R12	0.2526	0.5998	R27	0.2093	0.5873	R42	0.1346	0.1563
R13	0.237	0.8931	R28	0.147	0.2263	R43	0.1138	0.1469
R14	0.0949	0.8482	R29	0.1919	0.3374	Total Operating Time		25.5731
R15	0.3584	0.4146	R30	0.1826	0.4038			

Table 5. Operating time of relays for some faults

Fault Location	Primary Relay Operating Time (Sec)	Backup Relay Operating Time (sec)
F30	0.2917, 0.3946	0.4918, 0.9432, 1.1453
F43	0.1710, 0.3200	0.3715, 0.7539
F3	0.1325, 0.2554	0.3326, 2.6389, 0.9120, 3.0540
F19	0.3067, 0.3382	0.5067, 0.7090, 0.7069

5. CONCLUSION

In this paper, inter-trip links, impact on protection coordination of DOCRs is investigated. It is seen that inter-trip links locally decreases the operating time of relays and the neighbor relays become more sensitive. The proposed index successfully reflects the inter-trip impact and searches for optimum location of inter-trip links. Then, inter-trip links is incorporated in optimal coordination of DOCRs with an optimum allocation feature. The results indicate the capability of proposed index and method, which is verified through the exhaustive search algorithm.

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