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Protection coordination of directional overcurrent relays: new time current characteristic and objective function

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Abstract: Clearing power grid faults swiftly and selectively offers higher security, reliability and sustainability. Accomplishing this aim by deploying directional overcurrent relays (DOCRs) is one of the major challenges in meshed and multisource distribution networks. To overcome this challenge, the current study elaborates a new coordination strategy which concentrates on minimising overall operation time of relays. In this strategy, an auxiliary variable is added to classical operation time model of each DOCR. All the auxiliary variables are considered as coordination constraints which help to yield new and well-defined time current characteristics (TCCs). In other words, more flexibility is attained in adjusting relay's characteristic which helps to alleviate clearing time of faults. The obtained TCCs can be easily performed by numerical relays. In addition, a new objective function is defined to steer the relay settings towards optimal solutions conveniently. It was shown that the proposed approach not only reduces the operation time of relays, but also prevents miscoordinations. This approach demonstrates a non-linear programming model tackled by particle swarm optimisation algorithm. The effectiveness of the proposed approach is verified via 8-bus and IEEE 14-bus test systems and results are discussed in depth.

1 Introduction

Due to low cost and simplicity in implementation, deploying overcurrent relays is a common practice for protection system of distribution networks. Coordination of directional overcurrent relays (DOCRs) in multisource distribution networks is complex problem [1, 2] which yields higher operation time for relays in clearing faults. This is while, fast protection system plays vital role in minimising the level of power equipment damage, preventing the unintentional feeder or distribution generations disconnections, decreasing probability of instability and even enhancing the power quality metrics. Therefore, operation time of DOCRs is necessary for fast protection of these networks.

Several solutions have been suggested to meet the coordination problem of DOCRs in literatures. Trial and error methods have been utilised in [3, 4]. Despite improvements they are encountered with serious problems in changing conditions and huge computational efforts. Deterministic methods are also applied for the same mission which could provide reliable and accurate results [5]. However, these methods are in challenge with increased complexity [6] and thus, is not an efficient choice for real-scale networks. Linear programming techniques such as simplex, two-phase simplex and dual simplex have also been utilised in [7–10]. These methods are based on initial guess which increases probability of getting stuck in local minima [11]. Moreover, relay coordination problem is a non-convex and non-linear problem, therefore linear methods may not be efficient [12]. Heuristics methods have quickly gained popularity [13] and have shown great potential in solving relay coordination [14]. The implementation of different heuristics methods has been studied in [12–17]. Alam *et al.* in [14] presented a comprehensive comparative study among different meta-heuristic optimisation approaches. genetic algorithm (GA)-hybrid, particle swarm optimisation (PSO)-hybrid and hybrid gravitational search algorithm-sequential quadratic programming (GSA-SQP) algorithms are further explored in [18–20] for relay coordination. Some other researchers focus on improving evaluating part of optimisation process. Different objective functions (OFs) are presented in [21–23]. In [24–26] by deploying dual setting DOCRs, new backups for primary relays are defined. Although, the scheme with dual setting DOCRs provide faster operation in clearing faults, but using this kind of relays needs to assist communication links to guaranty proper protection scheme.

By deploying efficient time current characteristics (TCCs), more flexibility and extensibility can be attained in relaying which results in lower value for OFs. Numerical relays allow the users to set up arbitrary TCCs graphically, in table form [27, 28] and through adjusting the constant coefficients of relay operation function [29, 30] which paves the way for developing coordination strategies. In view of that, by observing some basic rules, the operator could easily encode these relays to reshape the relay's TCCs and hence, improve the protection quality. Based on this capability, new coordination strategies are proposed in [31, 32], namely user-defined. In such strategies, in addition to time dial setting (*TDS*) and plug setting (I_p), the other constant coefficients of TCC are considered as coordination constraints. Although the investigated literatures have been improved protection coordination metrics, still attaining a faster protection system is achievable with the aforementioned capability of numerical relays.

This study presents a new coordination strategy based on numerical relays which allow users to define arbitrary TCC. In this strategy, an auxiliary variable is added to the classical operation time model of each DOCR. Then, the auxiliary variables are considered as coordination constraints. These variables are taken into consideration at devising a new TCCs. Due to application of new TCCs in the devised strategy, coordination among relays and relays with instantaneous ones, if enabled, may be imperiled. Accordingly, such a strategy should entail restricting the minimum operation time of relays. So some necessary constraints are accommodated in the process of optimisation. Furthermore, the present study establishes a new insight into efficient OF development for the purpose of reducing the overall operating times of relays without any miscoordination.

The main contributions of proposed approach are listed as follows:

- A new protection coordination strategy is devised by deploying new TCCs;
- New TCCs observe basic rules of overcurrent relaying;

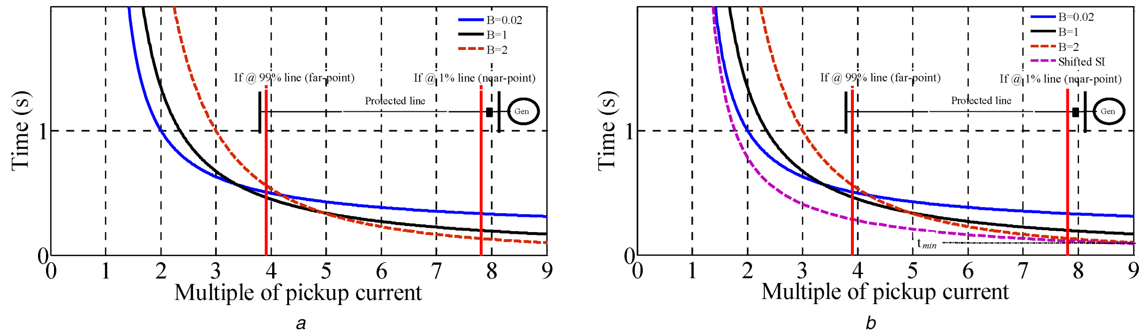

Fig. 1 *Typical distribution network*

- A new insight into efficient OF development is established;
- An efficient optimisation model is established caring the existing constraints;
- Remarkable reduction in total operation time of relays is achieved;
- There is no record of miscoordination in the proposed approach;
- The proposed approach does not imperil sensitivity of relay.

Coordination with single fault location may depreciate accuracy of protection coordination along the protected line especially in far-end locations. Hence, to enhance the coordination accuracy, coordination constraints are also considered for different fault location of lines [5, 31].

The established strategy reveals a non-liner optimisation problem which is tackled based on particle swarm optimisation algorithm. The ongoing study continues as follows. The proposed protection approach based on new TCCs is presented in Section 2. This section also sheds enough lights on the optimisation phase of the problem. The optimisation problem is formulated in Section 3. Section 4 addresses the test systems' specifications and articulates about the simulation setups. The investigated test cases and the obtained results are pointed out in Section 4. Eventually, Section 5 concludes the manuscript.

2 Proposed coordination strategy

2.1 New TCC

The operation time of DOCR is governed with an inverse function of the fault current which is passed through it. The function is represented as follows:

$$t = TDS\left(\frac{A}{(I_{\text{Fault}}/I_p)^B - 1}\right) \tag{1}$$

In conventional coordination strategy, *TDS* and I_p of relays are set up optimally during the optimisation process. The other coefficients *A* and *B* are tightened to a constant value [15]. *A* presents the constant for relay TCCs and *B* presents inverse time type. This is while, based on the capability of numerical relays, user-defined coordination strategy proposed in [31] is employed for DOCR coordination. In such strategy, in addition to TDS and I_p, the tightened coefficients are all together considered as continuous variable settings, which brings different TCC and so attains higher flexibility along and thereby, the overall operation time of relays is decreased. This fact can also be concluded from Fig. 1*a* that three different TCCs with different *B* are illustrated. These TCCs are plotted in minimum TDS and I_p. The obvious thing is, the operation time of relay along with the protected line with $B = 1$ and $B = 2$ is lower than the standard inverse characteristic ($B = 0.02$). Therefore, user-defined approach with more TCCs options provides faster protection system. Meanwhile, to coordinate DOCRs, some more useful TCCs can be described which are neglected in that strategy. Although, Fig. 1*a* shows that these TCCs have considerable distance with standard inverse characteristic during faults at near-end location, but due to high slop of these curves, by getting away from near-end location, this distance is reduced. So, this strategy can be improved by a new TCC with low slope curve. A new TCCs is illustrated in Fig. 1*b* by shifting down the standard inverse characteristic. As it can be seen, this TCC reduces the relay operation time not only in near-end location, but also along the protected line. To provide such feature for relays, an auxiliary variable (t_{off}) is added to classical TCC as follows:

$$t = TDS\left(\frac{A}{(I_{\text{Fault}}/I_p)^B - 1}\right) + t_{\text{off}} \tag{2}$$

By using this variable, relay's TCC can be moved down more than usual. As stated before, the obtained TCC with this function is able to implement by some commercial relays [27, 28]. After describing the optimal TCCs, they can be applied to numerical relays graphically or in table form. In fact, some more TCCs would be available which are very useful to alleviate operation time of relays. Although, defending new TCC with user-defined strategy gives more different TCCs, but it seems that more important TCCs which can be deployed by numerical relays is neglected.

For accommodating the constraints related to t_{off} of relays, defining a lower boundary for these variables are indispensable. Shifting down a TCC consumedly may imperil coordination between relays and relays with instantaneous ones. On the other hand, lower boundary of each auxiliary variables depends on the place of the respected relay in network since relays in different place experience different short circuit power. Thus, different relays will have different boundaries for these variables. What is more, the proposed coordination strategy will depend on networks and their topologies. Therefore, some rules should be defined to prevent the coordination strategy from dependency to network structure, as well as maintaining the protection system with no violations. To this end, the minimum operation time of each relays ($t_{\min}$) should be restricted in a pre-defined value during faults with maximum magnitude at the near-end location of line. In this case, not only the strategy will be independent from the place of relay, but also coordination between relays and instantaneous ones will not be at risk. Another key point to remember is that shifting down the characteristics may lead to horizontal axis crossing which can be observed in Fig. 2. Thus, it is able to cut down the relays operation time. Although the characteristics cross the horizontal axis, but the t_{off} value is adjusted in a way that $t_{\min}$ is guaranteed during faults at near-end location. That is, proper protection task is adjusted for the relay during faults along the protected line. However, for faults at adjacent line in behind, axis crossing is not important at all because the deployed relays are directional. To sum up, the proposed strategy can get negative values for the variable t_{off} and applies it to the optimisation process. However, the protection task along with the protected line does not face any problem.

2.2 Improving evaluation process

As stated earlier, the recent trend in relay coordination has been performed based on intelligent algorithms which are mainly centred on efficient OF design. In the earlier such as those presented in [21, 22], the magnitude of malfunctioning penalty lessens with a decrease on the negative part of discrimination time

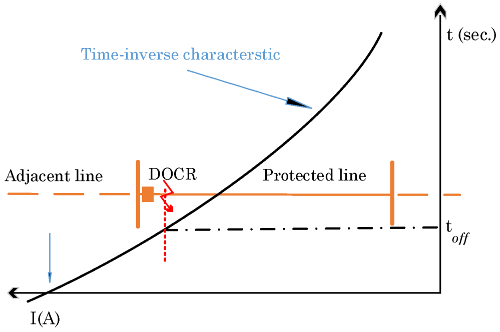

Fig. 2 *Relay characteristic along the protected line with negative t_{off}*

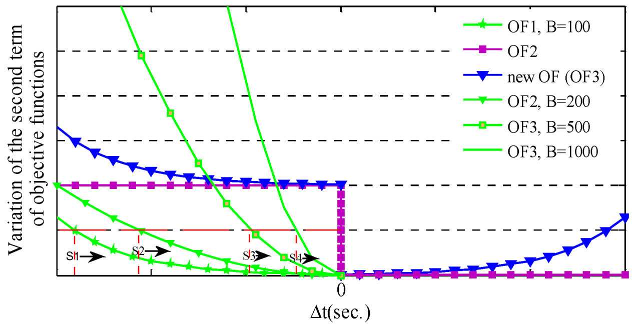

Fig. 3 *Variation ofthe second term of OFs*

(Δt) between the primary/backup (P/B) pair relays which is mathematically represented in (3)

$$\mathrm{OF1} = \alpha \sum_{i \in I} (t_i)^2 + \beta \sum_{k \in K} (\Delta t_k - |\Delta t_k|)^2 \tag{3}$$

$$\Delta t_k = t_{bk} - t_{pk} - CTI \tag{4}$$

where t indicates the operation time of relays. Moreover, i and k are the indices of all relays and all P/B pair relays, respectively. α and β are weighting factors. Moreover, I and K represent the sets of all relays, and P/B pair relays, respectively. CTI is the minimum gap between the operation time of primary relay and its backup one. When CTI is not fulfilled, it is possible that, the backup relay would operate sooner than the primary relay. This situation is called miscoordination.

With respect to (3), it can be obviously seen that the OF1 consists of two parts. The first part is considered to minimise the operating time of relays and the second part is considered to minimise the number of miscoordinations. As it can be seen when Δt is positive, the second term is zero, and when Δt is negative the second term has a value that is intended to remove the miscoordination. However, with respect to Fig. 3, which shows variation of the second term of OFs in the new method and old ones, it can be seen that for the OF1 case, the magnitude of penalty is very low for smaller $\Delta t'$s. For instance, if β is considered as 100 and $\Delta t = -0.05$, then the penalty magnitude would be equal to 1 which is small in comparison with the value of first term. This small value of penalty magnitude makes the algorithm go off the road and hence, it could not be successful to omit miscoordinations. This situation is the same for all $\Delta t'$s in area S1 in Fig. 3. On the other hand, by increasing β consumedly, the area S1 would be reduced to area S4, but it restricts optimisation algorithms to converge [23].

In [23], to overcome the aforementioned drawback of OF1, a new OF is proposed as follows:

$$\mathrm{OF2} = \alpha \sum_{i \in I} (t_i)^2 + \sum_{k \in K} \beta_k \times \mathrm{BC}_k \tag{5}$$

$$\mathrm{BC}_k = \begin{cases} 0, & \Delta t_k \geq \varepsilon \\ 1, & \Delta t_k \leq \varepsilon \end{cases} \tag{6}$$

OF2 has a similar formation to OF1, as it consists of two main parts. The first part is the exact replication of first part in OF1 and hence is overlooked. β in this OF is different for various P/B pair relays. It depends on the situation of network and the place of relay in it. Returning back to (6), BC is a binary variable whose status is determined through the evaluation of Δt with ε, which is determined as the threshold value. As it can be seen from Fig. 3, in this method the magnitude of the penalty factor is considered as a relatively high constant value to force the optimisation algorithm to counteract the aggregation of $\Delta t'$s in the negative side. Although β is different for various pair relays, but it has the same value for different magnitude of discrimination times. For example, for $\Delta t_k = -0.2$ and $\Delta t_k = -10$, it would have the same penalty value β_k. β_k is determined experimentally and is dependent on the network topology. Moreover, in these OFs, there is no force on positive discrimination time of relays. In this paper, the proposed OF innovatively deploys an exponential penalty term to steer the solutions toward the desired operating region. This term is inspired from previous two OFs. The proposed penalty curve is shown in Fig. 3. As it can be seen, the new term of OF covers the problem of lower value discrimination time by increasing penalty value for negative $\Delta t'$s, is varied by different discrimination time, has the penalty value for positive discrimination times, is independent from network topology and consequently steers the variables to optimal solutions successfully.

3 Problem formulation

As clarified earlier, in conventional coordination strategy, TDS and I_p of relays must be set up optimally. In the user-defined coordination strategy, in addition to TDS and I_p, the other coefficients of TCCs A and B are also optimised. While, the proposed approach aims at optimising the variables TDS, I_p and auxiliary variable t_{off} to yield in an optimal protection strategy through the enhanced TCCs. The final goal, declared in (7) and (8), is to minimise the overall operation time of relaying task. As well, effective penalty factors are integrated to the main objective to steer the optimisation engine towards the desired regions

$$\mathrm{OF3} = \sum_{d \in D} \left[\alpha \sum_{i \in I} (t_{i,d})^2 + \beta \sum_{k \in K} \mathrm{BC}_{k,d} + \gamma_1 \sum_{k \in K} \mathrm{e}^{\gamma_2 |\Delta t_{k,d}|} \right] \tag{7}$$

$$\mathrm{BC}_{K,d} = \begin{cases} 0, & \Delta t_{k,d} \geq \varepsilon \cong 0 \\ 1, & \Delta t_{k,d} \geq \varepsilon \cong 0 \end{cases} \tag{8}$$

In this OF, γ_1 and γ_2 are weighting factors. d is the indices of fault points and D represents the set of fault points. Each DOCR complies with one TCCs as follows:

$$t_{i,d} = TDS_i \left(\frac{A_i}{(I_{\mathrm{Fault}_d}/I_{p_i})^{B_i} - 1} \right) + t_{\mathrm{off}_i}, \quad \forall i, d \tag{9}$$

The coordination constraints should be pursued carefully to end in a reliable and accurate protection strategy. The coordination time interval (CTI) between operation time of primary and backup relays should be established in all P/B pair relays as follows:

$$\Delta t_{k,d} = t_{b\,k,d} - t_{p\,k,d} - CTI \geq 0, \quad \forall k, d \tag{10}$$

By considering identifier d and set D in this formulation, when coordination problem is done for multi-point faults, OF would aggregate overall operation time of relays in different fault locations and also selectivity constraints would be considered in all fault locations between all pair relays.

The parameters that are shaping the TCC should be properly capped within their corresponding intervals. Hence, suitable constraints are considered for TDS, I_p, A, B and t_{off} in (11)–(15) with respect to different coordination strategy

$$TDS_{\min} \leq TDS_i \leq TDS_{\max}, \quad \forall i \tag{11}$$

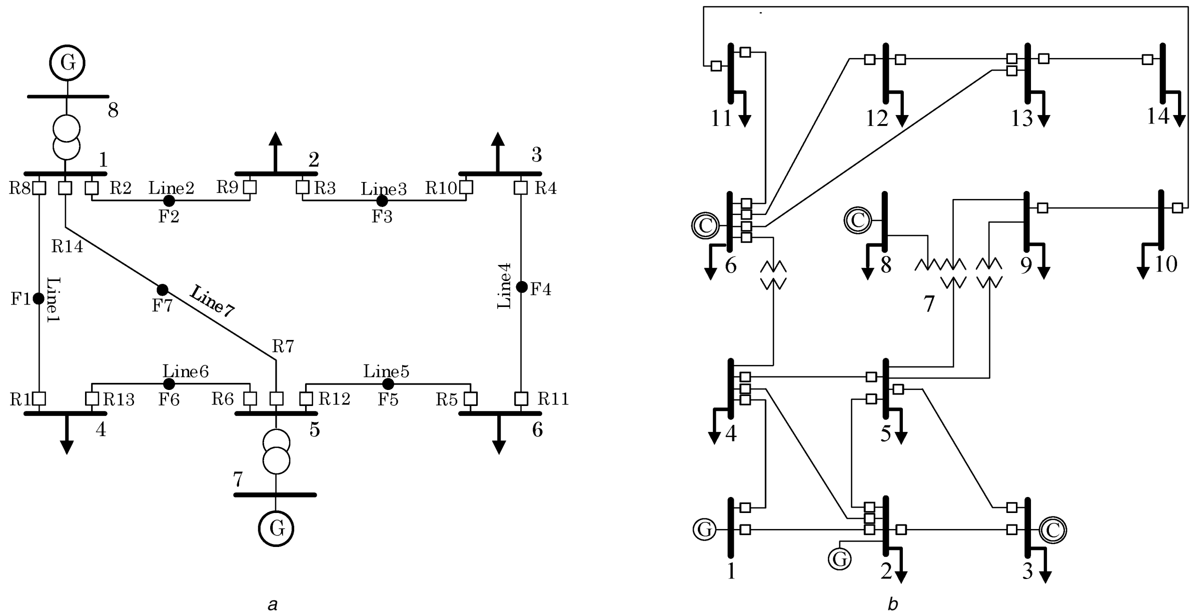

Fig. 4 *Single line diagram of test systems*
(a) *8-bus system,* ***(b)*** *IEEE 14-bus test system*

$$Ip_{\min} \le Ip_i \le Ip_{\max}, \quad \forall i \tag{12}$$

Constraints (11) and (12) are the main basis for extracting the required settings of conventional coordination strategies

$$A_{\min} \le A_i \le A_{\max}, \quad \forall i \tag{13}$$

$$B_{\min} \le B_i \le B_{\max}, \quad \forall i \tag{14}$$

Constraints (11)–(14) are all together for extracting the required settings of user-defined coordination strategies

$$t_{\text{off min}} \le t_{\text{off } i} \le t_{\text{off max}}, \quad \forall i \tag{15}$$

Constraints (11)–(12) and (15) are all together for extracting the required settings of proposed coordination strategies.

Eventually, to assure the security of the proposed protection strategy, the operation time of each relay should also be regarded. To this end, the following constraint considers the minimum and maximum permissible times. The minimum operation time also guarantees the coordination between relays and instantaneous ones

$$t_{\min} \le t_i \le t_{\max}, \quad \forall i \tag{16}$$

4 Test system evaluations and general discussions

4.1 System specifications

8-bus and IEEE 14-bus systems are considered to evaluate the performance of the proposed strategy. Both are typical multisource meshed systems which are proper for such studies. The single diagram of 8-bus test system is shown in Fig. 4*a*. It consists of 14 DOCRs and 20 pair relays. Detailed data of this test system could be accessed in [33]. *TDS* is assumed between 0.05 and 1.1. The single diagram of IEEE 14-bus system is shown in Fig. 4*b*. It mainly consists of 30 DOCRs and 50 pair relays. Detailed data of this test system are given in [32]. *TDS* is assumed between 0.1 and 3.2.

In both, I_p is assumed between $1.1 \times I\text{Load}_{\max}$ and $1.5 \times I\text{Load}_{\max}$. On the other hand, when $I_{\text{Fault}_{\min}}$ is lower than $1.5 \times I\text{Load}_{\max}$, $I_{p\max}$ will be equal to $I_{\text{Fault}_{\min}}$, also when $I_{\text{Fault}_{\min}}$ is lower than $I_{p\min}$, I_p will be equal to $I_{p\min}$. *CTI* takes a value between 0.2 and 0.5 s [31]. Here, *CTI* is assumed 0.3 s in the first case and 0.2 s in the second case. Regarding the relays' characteristics in user-defined strategy, the minimum values of parameters *A* and *B* are determined as 0.14 and 0.02, whereas the maximum limits are assigned as 13.5 and 1, respectively. t_{off} in the proposed strategy is among −10 and 10. To assure the security of the proposed protection strategy, the constraints in (16) for the minimum and maximum permissible times are appointed by 0.1 and 2.5 s, respectively [31].

4.2 Numerical results

The performance of proposed coordination strategy is evaluated in two different cases. In the first case, 8-bus system and in the second manner IEEE 14-bus system are deployed as testbeds. Both of the test systems are implemented in DIgSILENT PowerFactory 14.3.1 platform which is a well-developed software for bulk power system studies. In each case, three different coordination strategies are compared; namely conventional coordination strategy, user-defined coordination strategy and the proposed one. In the conventional coordination strategy, standard inverse characteristics are deployed for relays, and thereby *TDS* and I_p are variables. In the user-defined coordination strategy, there are more options for selecting characteristics. In this strategy, there are four variables, namely *TDS*, I_p, *A* and *B*. While, the variables in the proposed strategy are *TDS*, I_p and t_{off}. Coordination with single fault location may depreciate accuracy of protection coordination along the protected. Hence, to enhance the coordination accuracy, coordination constraints are considered for faults at near-end and far-end location of line [5].

4.2.1 First case: numerical studies on 8-bus test system: At the outset, the conventional coordination strategy is modelled and solved optimally for faults at near-end and far-end locations of protected lines. The obtained optimal settings are reported in Table 1. The operation time of relays are also reflected in Table 1. The sum of operation time of primary and backup relays in the two fault locations is 81.54 s. All pair relays satisfy *CTI* and there is no miscoordination. The user-defined coordination strategy is carried out to coordinate relays optimally for the faults at same points. Optimal settings and the obtained operation time of relays are given in Table 2. As it can be seen, the coordination constraints are properly satisfied and no record of miscoordination is noticed. The overall operation time of relays in this strategy is 55.1 s which is decreased 32.41% with respect to conventional one. User-defined coordination strategy provides more TCC options and results faster protection system.

The proposed coordination strategy is applied on the same test system. Here, in addition to the typical variables *TDS* and I_p, t_{off} is

Table 1a Continued

Optimal setting of DOCRs					
Relay no.	Parameter		Relay no.	Parameter	
	TDS	I_p		*TDS*	I_p
1	0.3727	0.1560	8	0.4535	0.1635
2	0.3738	0.2490	9	0.1436	0.1770
3	0.2859	0.1875	10	0.2728	0.1210
4	0.1565	0.2700	11	0.3378	0.2025
5	0.1183	0.1935	12	0.4822	0.1830
6	0.4816	0.1710	13	0.3163	0.1875
7	0.3500	0.2115	14	0.3395	0.2490

Table 1b Results of conventional strategy: case 1

Operation time of DOCRs					
Pair relays		Fault point			
		Near-end		Far-end	
PR[a]	BR[b]	t_{primary}	t_{backup}	t_{primary}	t_{backup}
2	1	0.8232	1.5371	0.9595	2.8537
14	1	0.8187	1.5509	1.2509	1.5509
3	2	0.6636	0.9636	0.8673	1.3011
4	3	0.5718	0.8718	0.7604	1.1015
5	4	0.4673	0.7673	1.3621	4.0326
6	5	0.9693	1.4602	1.1853	—
7	5	0.7965	1.4837	1.1837	1.4837
1	6	0.8914	1.1914	1.5098	2.0643
2	7	0.8232	1.1974	0.9595	1.9444
8	7	0.9005	1.2005	1.1277	—
13	8	0.8340	1.1340	1.4408	1.8916
8	9	0.9005	1.5297	1.1277	—
14	9	0.8187	1.5509	1.2509	1.5509
9	10	0.5213	0.8213	1.4342	1.7549
10	11	0.6044	0.9044	0.8148	1.3084
11	12	0.7938	1.0938	0.9008	1.2357
7	13	0.7965	1.4837	1.1837	1.4837
12	13	0.9622	1.4689	1.0912	2.7156
6	14	0.9693	1.2693	1.1853	—
12	14	0.9622	1.2657	1.0912	2.0147

[a]Primary relay.
[b]Backup relay.

Table 2a Continued

Optimal setting of DOCRs				
Relay no.	Parameter			
	TDS	I_p	*A*	*B*
1	1.1000	0.1560	3.8895	1
2	1.1000	0.2490	6.6763	1
3	1.1000	0.1875	4.2081	1
4	1.1000	0.2700	1.2557	1
5	0.8506	0.1935	0.8163	1
6	0.9132	0.1710	9.0724	1
7	1.1000	0.2115	3.8163	1
8	0.5858	0.1635	13.5000	1
9	0.3850	0.1770	2.3745	1
10	1.0349	0.1210	3.3440	0.9410
11	1.1000	0.2025	5.4131	1
12	1.1000	0.1830	11.1981	1
13	0.6564	0.1875	4.7813	1
14	1.0404	0.2490	3.7284	1

also considered in optimisation process. In order to provide TCCs with low slope, parameters *A* and *B* are considered 0.14 and 0.02, respectively. Table 3 represents the optimal settings. As it can be deduced, most of the relays prefer to get negative values for t_{off}. Operation time of relays for faults at near-end and far-end locations

Table 2b Results of user-defined strategy: case 1

Operation time of DOCRs					
Pair relays		Fault point			
		Near-end		Far-end	
PR[a]	BR[b]	$t_{primary}$	t_{backup}	$t_{primary}$	t_{backup}
2	1	0.3531	0.9932	0.5550	2.9019
14	1	0.2455	1.0113	0.7113	1.0113
3	2	0.2616	0.5616	0.5419	1.1874
4	3	0.2488	0.5488	0.4403	0.9338
5	4	0.1477	0.4477	0.8371	4.4399
6	5	0.2973	0.9171	0.5560	—
7	5	0.2235	0.9362	0.6362	0.9362
1	6	0.2642	0.5642	0.9576	2.0774
2	7	0.3531	0.6531	0.5550	1.6993
8	7	0.2711	0.6570	0.5467	—
13	8	0.2553	0.5553	0.8855	1.8781
8	9	0.2711	0.9927	0.5467	—
14	9	0.2455	1.0113	0.7113	1.0113
9	10	0.1623	0.4623	0.9090	1.9736
10	11	0.2052	0.5052	0.4536	1.2149
11	12	0.3492	0.6492	0.4998	0.9269
7	13	0.2235	0.9362	0.6362	0.9362
12	13	0.4295	0.9187	0.6444	2.5200
6	14	0.2973	0.7340	0.5560	—
12	14	0.4295	0.7295	0.6444	1.7562

[a]Primary relay.
[b]Backup relay.

Table 3a Continued

Optimal setting of DOCRs			
Relay no.	Parameters		
	TDS	I_p	t_{off}
1	0.4963	0.1144	−0.9668
2	0.9824	0.1826	−1.8593
3	0.5186	0.1375	−0.9852
4	0.3413	0.1980	−0.9672
5	0.1261	0.1419	−0.3218
6	0.7906	0.1254	−1.3522
7	0.3339	0.1551	−0.5862
8	0.7081	0.1199	−1.1845
9	0.1604	0.1298	−0.3986
10	0.3773	0.1210	−0.7361
11	1.1000	0.1485	−2.2175
12	1.1000	0.1342	−1.8260
13	0.3897	0.1375	−0.8146
14	0.3732	0.1826	−0.7084

are also given in Table 3. The coordination constraints are properly satisfied and no record of miscoordination is noticed. The sum operation time of relays in this strategy is 38.77 s which is decreased 52.5 and 29.6% compared with conventional and user-defined coordination strategy. This reduction is obtained due to the flexibility of proposed approach which is provided with the new TCCs. This coordination strategy reduces operation time of primary and backup relays not only in near-end location but also in far-end location. For instance, the obtained result of user-defined strategy shows that, the overall operation time of primary and backup relays in near-end and far-end locations are 3.71, 14.78, 9.17 and 27.4 s. This is while, these values related to proposed strategy are 1.49, 10.77, 6.74 and 19.77 s which attest the superiority of proposed strategy. The proposed strategy with low slope TCC provides faster protection. The minimum operation time which is reported in Table 3 is 0.1 s. It shows that the proposed strategy will not imperil coordination between relays with instantaneous ones if enable. Furthermore, by comparing I_p of relays in different approaches, it is recognised that by using the proposed approach sensitivity of relays is enhanced by decreasing I_p of relays.

Illustrative comparisons are considered to weigh the proposed strategy against conventional and user-defined methods. Figs. 5*a–d* demonstrate the operating times of primary and backup relays in near-end and far-end points. These figures contribute to a superior performance obtained based on the proposed approach. As it can be inferred, by using the new TCC higher reduction is attained in operating time of relays.

4.2.2 Second case: numerical studies on IEEE 14-bus test system: In the previous case, the proposed approach was evaluated on a simple test system. Here to evaluate the superiority of proposed approach on large-scale networks, IEEE 14-bus system is chosen as testbed which is more complicated than that of 8-bus

Table 3b Results of proposed strategy: case 1

Operation time of DOCRs					
Pair relays		Fault point			
		Near-end		Far-end	
PR[a]	BR[b]	$t_{primary}$	t_{backup}	$t_{primary}$	t_{backup}
2	1	0.1000	0.7537	0.3913	1.8550
14	1	0.1000	0.7668	0.4668	0.7668
3	2	0.1000	0.4000	0.3938	1.0857
4	3	0.1000	0.4000	0.3899	0.7119
5	4	0.1000	0.4000	0.6353	3.1206
6	5	0.1000	0.6799	0.3920	—
7	5	0.1000	0.6902	0.3902	0.6902
1	6	0.1000	0.4000	0.7278	1.4795
2	7	0.1000	0.4000	0.3913	0.8941
8	7	0.1000	0.4022	0.3921	—
13	8	0.1000	0.4000	0.6540	1.2939
8	9	0.1000	0.7560	0.3921	—
14	9	0.1000	0.7668	0.4668	0.7668
9	10	0.1000	0.4000	0.7059	1.6914
10	11	0.1000	0.4000	0.3910	1.3985
11	12	0.1101	0.4280	0.3906	0.6906
7	13	0.1000	0.6902	0.3902	0.6902
12	13	0.1787	0.6778	0.4230	1.5961
6	14	0.1000	0.4816	0.3920	—
12	14	0.1787	0.4787	0.4230	1.0353

[a]Primary relay.
[b]Backup relay.

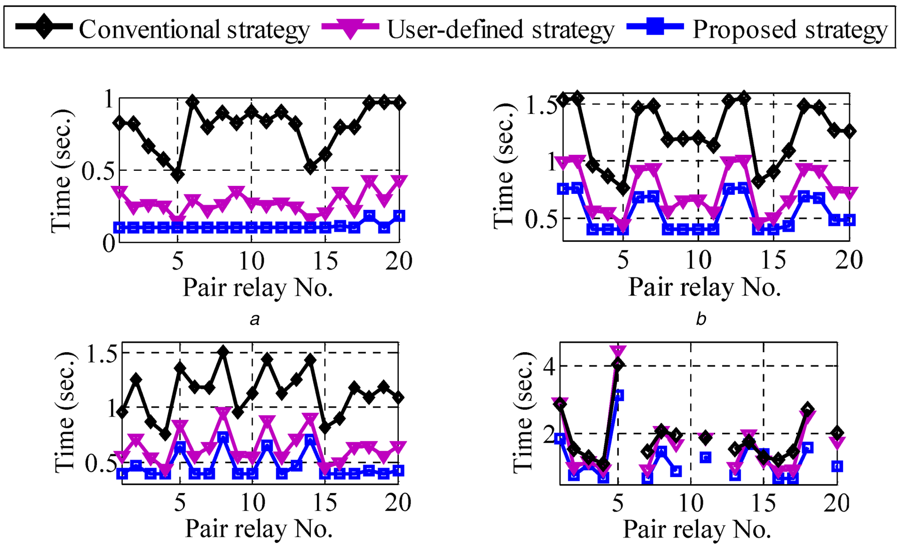

Fig. 5 *Comparison of the proposed strategy versus the conventional strategies in case 1. Operation time of relays for*
(a) Primary relays in near-end, ***(b)*** Backup relays in near-end, ***(c)*** Primary relays in far-end, ***(d)*** Backup relays in far-end

system. In this system, like pervious one, the proposed coordination strategy is compared against conventional and user-defined ones. Coordination processes are executed in near-end and far-end locations of protected lines. In relays coordination process based on conventional strategy, the optimal settings and the overall operation time of relays are given in Table 4. With respect to this strategy, the sum of operation time of relays is 149.062 s. As well, the optimal settings and the overall operation time of relays with user-defined coordination strategy on this test system are reported in Table 5. The sum operation time of relays is 95.582 s which is decreased 35.58% with respect to conventional strategy.

Optimal settings obtained from proposed coordination strategy are given in Table 6. As it can be deduced, in this case like pervious one, the parameter t_{off} gets negative value. Overall operation time of relays are also given in Table 6 which shows a notably reduction in operation time of relays. This reduction offers higher security, reliability and sustainability. The sum of operation time of relays is 78.217 s which is decreased 47.5 and 18.2% compared with conventional and user-defined coordination strategy.

Here again, illustrative comparisons are considered to highlight the performance of proposed strategy against the conventional and user-defined methods. Figs. 6*a–d* show the operating times of primary and backup relays in near-end and far-end points. These figures demonstrate that, by using the optimal settings which are reported in Table 6, a fast-response protection scheme in clearing faults is achieved. The minimum operation time which is seen in Fig. 6 is 0.1 s. It confirms that the proposed strategy will not imperil coordination between relays with instantaneous ones if enable.

Table 4 Result of conventional strategy: case 2

Optimal setting of DOCRs					
Relay no.	Parameters		Relay no.	Parameters	
	TDS	I_p, kA		*TDS*	I_p, kA
1	0.1368	0.3423	16	0.3267	0.1729
2	0.1411	0.3402	17	0.4808	0.1407
3	0.1397	0.3276	18	0.1000	0.1407
4	0.1000	0.3276	19	0.3866	0.4069
5	0.1214	0.3991	20	0.1401	0.4069
6	0.1000	0.3224	21	0.5662	0.1456
7	0.1631	0.2468	22	0.4169	0.1176
8	0.1008	0.2457	23	0.4388	0.2184
9	0.1719	0.2262	24	0.3138	0.2095
10	0.1065	0.2262	25	0.5118	0.0884
11	0.2095	0.1071	26	0.5595	0.0884
12	0.1861	0.1092	27	0.5352	0.0377
13	0.1443	0.2846	28	0.3713	0.0377
14	0.1511	0.3549	29	0.4670	0.1274
15	0.5654	0.1729	30	0.4213	0.1274
Overall operation time of relays				149.062 s	

Table 5 Result of user-defined strategy: case 2

Optimal setting of DOCRs									
Relay no.	Parameters				Relay no.	Parameters			
	TDS	I_p, kA	*A*	*B*		*TDS*	I_p, kA	*A*	*B*
1	0.1344	0.3423	0.1400	0.0200	16	3.2000	0.1397	0.4218	0.5913
2	0.1405	0.3402	0.1405	0.0200	17	1.2116	0.1407	1.4647	0.5301
3	0.1000	0.3276	0.1400	0.0207	18	0.1000	0.1407	0.1400	0.0427
4	0.4131	0.4056	0.3968	0.3860	19	3.2000	0.3287	1.6432	0.9195
5	1.8018	0.3991	0.5907	0.8021	20	0.5990	0.4069	0.4959	0.6401
6	1.0792	0.3224	1.0521	1.0000	21	3.2000	0.1456	6.2437	1.0000
7	0.1615	0.2468	0.1414	0.0200	22	0.1295	0.1176	0.1539	0.0200
8	0.9477	0.2457	0.3489	0.3724	23	3.2000	0.2184	1.9885	1.0000
9	3.2000	0.1827	0.4908	0.7311	24	1.8877	0.2133	1.5522	1.0000
10	2.0649	0.2262	0.5406	0.8045	25	3.2000	0.0884	5.4793	1.0000
11	0.1641	0.1071	0.1400	0.0200	26	3.2000	0.0884	5.1654	1.0000
12	2.0957	0.1092	0.2614	0.3862	27	2.2557	0.0305	4.7407	0.8668
13	0.1000	0.2846	0.1400	0.0208	28	1.7902	0.0305	1.7362	0.5283
14	2.8053	0.2867	0.7246	0.8654	29	2.0735	0.1274	4.4972	1.0000
15	2.5407	0.1729	5.5838	1.0000	30	2.3271	0.1274	2.1998	1.0000
Overall operation time of relays						95.582 s			

4.2.3 Results validation: As mentioned earlier, a successful OF is developed to steer setting of relays toward optimal solutions. Here, the proposed OF is compared via OF2 to validate the performance of new OF. OF3 and OF2 are used for relays coordination in IEEE 8-bus test system and IEEE 14-bus test system with conventional and proposed coordination strategy. Results are given in Table 7. As it can be seen, higher reduction is attained by the proposed OF in operation time of relays.

Here, to show the importance of the new OF in reducing the overall relay operating time without influencing largely the sensitivity of relay, Fig. 7 is considered in comparing plug setting of relays which are obtained from different OFs. This figure demonstrates the performance of the established OF with regard to different coordination approaches. Fig. 7*a* shows plug setting of relays with different OFs with conventional coordination strategy and Fig. 7*b* shows plug setting of relays with different OFs with proposed coordination strategy. In this figure, plug settings of relays are represented in horizontal axes, sequentially. As can be seen, the proposed OF contributes to equal or lower plug settings and hence sensitivity of relays would not imperil with new OF.

5 Concluding remarks

Facing with an intricate task in interconnected networks, this paper established a new strategy for optimal coordination of DOCRs aims at achieving a fast and secure protection scheme. The new strategy presents new TCCs and therefore higher flexibility is achieved. In proposed strategy, an auxiliary variable is added to classical operation time model of each DOCR. All the auxiliary variables are then considered as coordination constraints which yields well-defined TCCs and results faster protection systems. In addition, a new OF is defined to steer the relay settings towards optimal solutions conveniently. The proposed strategy was compared against the conventional and user-defined coordination strategy in two cases with two different test systems. In the first case, the total operation time of relays is reduced 52.5 and 29.6% compared with conventional and user-defined coordination strategy. In the second one, the total operation time of relays is reduced 47.5 and 18.2% with respect to conventional and user-defined coordination strategy. Based on the simulation studies, the proposed methodology can attain an effective and reliable coordination for fast fault clearing purposes.

Table 6 Result of proposed strategy: case 2

Optimal setting of DOCRs							
Relay no.	Parameters			Relay no.	Parameters		
	TDS	I_p, kA	t_{off}		*TDS*	I_p, kA	t_{off}
1	0.1000	0.3423	−0.0451	16	0.1283	0.1397	−0.0294
2	0.1000	0.3402	−0.1197	17	0.3373	0.1407	−0.3723
3	0.1000	0.3276	−0.0794	18	0.1000	0.1407	−0.1211
4	0.1000	0.3276	−0.1497	19	0.3602	0.3287	−0.5269
5	0.2140	0.3224	−0.3428	20	0.1000	0.3287	−0.1887
6	0.1000	0.3224	−0.1801	21	1.2285	0.1176	−1.7193
7	0.1000	0.2468	−0.0558	22	0.1000	0.1176	0.0738
8	0.1000	0.2457	−0.1243	23	0.3312	0.2184	−0.4608
9	0.1773	0.1827	−0.2099	24	0.2777	0.1764	−0.5801
10	0.1105	0.1827	−0.1254	25	1.3776	0.0714	−1.9078
11	0.1000	0.1071	0.1790	26	1.5990	0.0714	−2.3940
12	0.2382	0.1092	−0.3143	27	0.5903	0.0305	−0.6985
13	0.3216	0.2846	−0.7023	28	0.7372	0.0305	−0.7710
14	0.2460	0.2867	−0.4682	29	0.3570	0.1274	−0.4800
15	0.6685	0.1729	−0.9057	30	0.5170	0.1274	−0.9155
Overall operation time of relays					78.217 s		

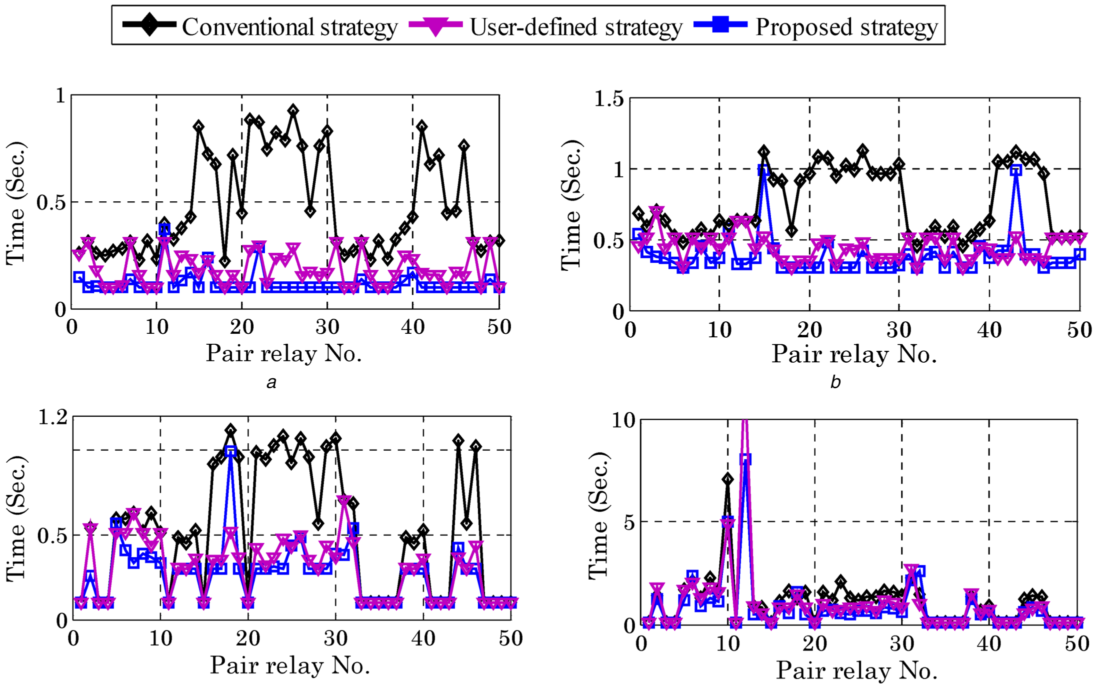

Fig. 6 *Comparison of the proposed strategy versus the conventional strategies in case 2. Operation time of relays for*
(a) Primary relays in near-end, ***(b)*** Backup relays in near-end, ***(c)*** Primary relays in far-end, ***(d)*** Backup relays in far-end

Table 7 Overall operation time of relays attained by different OFs in different cases

Test system	OF no.	Conventional coordination strategy				Proposed coordination strategy			
		Primary		Backup		Primary		Backup	
Near-end	Far-end	Near-end	Far-end	Near-end	Far-end	Near-end	Far-end		
8-bus	OF2	12.87	18.21	27.89	31.04	1.60	6.82	10.73	22.20
	OF3	10.61	15.89	24.75	30.29	1.49	6.74	10.77	19.77
14-bus	OF2	26.031	27.197	42.055	70.128	6.539	12.476	20.584	42.370
	OF3	23.832	24.523	37.553	63.155	5.939	11.711	19.290	41.277

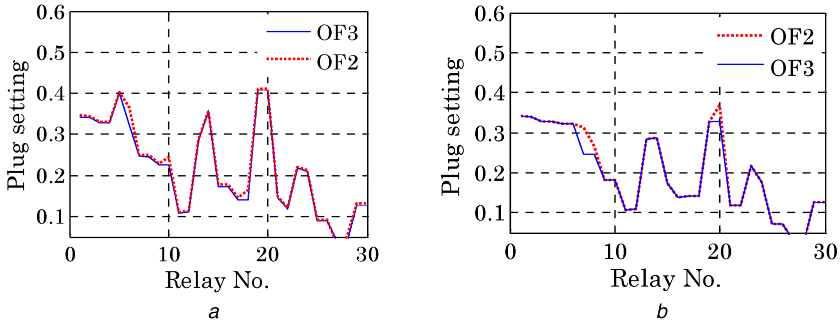

Fig. 7 *Comparison of OF3 versus OF2. Plug setting of relays of IEEE 14-bus system with*
(a) Conventional coordination strategy, ***(b)*** Proposed coordination strategy

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