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# A New Formulation for Coordination of Directional Overcurrent Relays in Interconnected Networks for Better Miscoordination Suppression

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A safe and reliable protection system in distribution networks, specifically, those hosting distribution generation units, needs a robust over-current protection scheme. To avoid unintentional DG disconnection during fault conditions, a protection system should operate quickly and selectively. Therefore, to achieve this aim, satisfying coordination constraints are important for any protection scheme in distribution networks; these pose a challenging task in interconnected and large-scale networks. In this paper, a new coordination strategy, based on the same non-standard time-current curve for all relays, in order to find optimal coordination of directional over-current relays, is proposed. The main aim is to reduce violations, especially miscoordination between pair relays. Besides this, the overall time of operation of relays during primary and backup operations should be minimized concurrently. This work is being tackled based on genetic algorithms and motivated by the heuristic algorithm. For the numerical analysis, to show the superiority of this coordination strategy, the IEEE 30-bus test system, with a mesh structure and supplemented with distributed generation, is put under extensive simulations, and the obtained results are discussed in depth.

**Keywords:** Distribution network, Over-current protection problem, Directional relays, Multi-source networks, Distribution generation

## 1. INTRODUCTION

Over-current relays (OCRs) are economical; so they have been well-recognized as the key building blocks of protection schemes in distribution networks. In this way, coordination between pair relays is the prerequisite of accurate, selective, fast, and reliable isolation of faulty sections throughout the network [1]. The traditional distribution networks are commonly radial, where the load flow is typically unidirectional. Consequently, the conventional OCRs are sufficient for efficient protection plans in this sort of network [1]. In contrary, for mesh interconnected distribution networks with penetrating distributed generations (DGs), the power flow would be definitely bidirectional; hence the conventional coordination would not be efficient for this sort of network [2]. This is where the emergent notion of smart distribution grids and its real-world implementations has paved the way to the vast penetration of efficient power production units, such as DGs, in the territory of distribution networks [3]. Being supplemental to these networks, although DGs have technical and economical merits, they would impose some operating bottlenecks as well. One of the other concerns of penetration of DG units is the increase of the short-circuit level of the networks, which leads to changes in the magnitude of fault currents. DGs' fault-current contribution depends on the type of DG unit; so the type of DG connected to the distribution network is important.

Inverter-based DG units have a negligible impact on coordination of relays, because of the controller limiters, which let the fault current reach approximately 1 or 2 per unit. In contrast, directly connected conventional synchronous generators (DCSG) contribute in fault current more than the other types of DGs do. Therefore in this paper, for simplicity, all DGs are considered to be

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the DCSG type [4].

Nowadays, digital microprocessor-based over-current relays with several integrated features and more power capabilities are more preferred than are conventional electromechanical over-current relays. By the outlined scope, deployment of directional OCRs (DOCRs) as a type of simple and technically justified digital relays is considered herein for the sake of achieving safe operation of distribution networks with DCSG-type DGs [5]. Although using DOCRs in distributed networks as the main protection was useful and improved reliability, up to now, coordination of DOCRs to satisfy all constrains, in interconnected and large-scale distribution networks, was one of the main challenges in protection of distribution systems.

Nowadays, heuristic algorithms are used widely in power-system problems [6-8]. To coordinate DOCRs to minimize the number of miscoordinations and the overall time of operation of all relays, many efforts have been discussed in the literature. To this end, versatile optimization methods, including trial-and-error methods, deterministic approaches, and heuristics techniques, have been used to find the optimal setting of relays, time-dial settings (*TDS*), and plug settings (*Ip*) to satisfy coordination constraints and minimize the overall relay operating time [9, 15]. The communication potentials in digital relays are used to propose a communication-based protection scheme in [16, 17]. In some works [such as 18], heuristics methods are improved to achieve the optimal setting. In [19] the authors tried to solve the optimization problem by some "expert rules". The expert rules have been considered in objective function, which is minimized by GA. Expert rules in that work depend on the structure of the network. In [20] the optimization problem is formulated after splitting the network. That work, like [19], depends on network topology. The authors in [21] have contributed to this field by proposing a GA NLP approach for optimum coordination of DOCRs. Following this survey, an adaptive approach is proposed to reduce the number of miscoordinations and the overall relay operating time. In the established mechanism, instead of using one population in each iteration, the process proposes the application of some subpopulations. Comparing the obtained results with that of the GA NLP method, although the volume of miscoordinations has been reduced, still the amount remaining is high and not suitable. Most of the literature coordinates DOCRs by adjusting *TDS* and *Ip*, in which, for all relays, an inverse-time curve is chosen for the time/current characteristics, whereas many commercial digital relays give the option to define the relay curve between standard characteristics. Therefore, Moravej et al. in [22], by considering time-dial settings and pickup current; have defined some other parameters of relay characteristics in the forming of chromosomes. They let the optimization engine choose the relay curve from three options: standard inverse (SI), very inverse (VI), and extremely inverse (EI). In the sequel, they have implemented NSGA-II as the optimization engine. Although demonstrating improved performance, the proposed approach is not likely to eliminate the miscoordinations [23]. To improve this scheme in [24], based on digital relays, a relay curve is defined by GA between standard time/current characteristics. By defining different time/current characteristics for each relay, the overall time of operation of relays is reduced significantly, but the number of miscoordinations is increased. To solve this matter, the optimization problem is defined for different points of faults, but this scheme is not likely to eliminate the miscoordinations [25]. In this paper, a new coordination strategy is proposed, based on digital relays, and takes into consideration user-defined curves. However, the time/current characteristics for all relays are considered to be the same and are tackled to be defined by GA. The coordination problem is formulated in such a way that the relay-like conventional strategy has two setting (*TDS* and *Ip*). In addition, two other settings are considered in order to choose the optimal curve for all relays that include the coordination problem. Taking into account the addressed issues, the present study intends to propose an efficient method, based on GA, intended for the protection of interconnected distribution networks hosting DCSG DG units.

In this paper a new protection scheme for dual-setting DOCRs is proposed. On this scheme the objective is to:

- Minimize the overall time of operation of primary and backup relays for faults at different locations;
- Minimize the number of miscoordinations.
- Minimize the sum of the discrimination times of pair relays.

"Miscoordination" is an expression used to show that selectivity is not fulfilled. In other words, "miscoordination" means that the coordination between the pair relay is not satisfactory, and that backup relays may act simultaneously or sooner than the primary relay,

For the numerical analysis, the IEEE 30-bus test system equipped with DCSGs is chosen as the test distribution system to implement a new idea to show the efficiency of this coordination strategy to minimize the overall time of operation of relays during primary and backup operations and the number of miscoordinations. All relays of the networks are DOCRs. This optimization problem is formulated as a nonlinear programming problem, where two settings of each relay and two other settings for all relays are determined to be variable in optimization process. As in most of the literature, the strategy of adjusting two *TDS* and *Ip* is considered to be a conventional strategy and will be referred to throughout the paper with the same name. In section 2, the proposed idea is discussed. Section 3 describes the system and simulation setup. Section 4 is for problem formulation. Section 5 is the result and analysis part, and the last section concludes the paper.

## 2. PROPOSED COORDINATION STRATEGY

### 2.1 Initial steps in literature

Inverse time over-current relay characteristics at *TDS*=1 and 0.1 are based on IEC 60255, as shown in Fig .1. The characteristic function for representing the relay's performance, based on the IEC

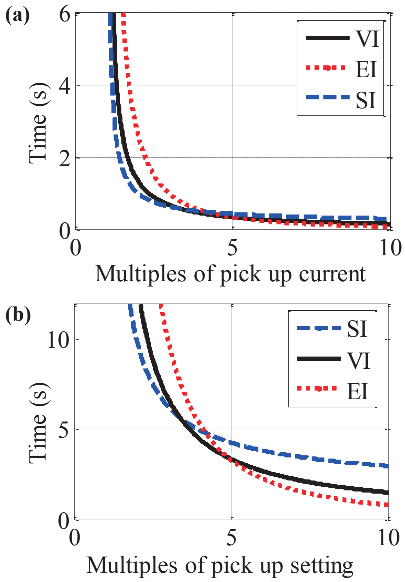

Fig. 1. IEC 60255 inverse time overcurrent relay characteristics at (a) *TDS*=0.1 and (b) *TDS*=1.

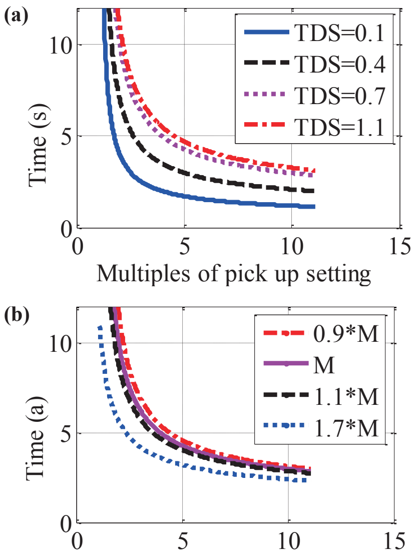

Fig. 2. Standard inverse relay curve for different (a) *TDS* and (b) *Ip*.

Table 1. Type of relays time/current characteristics.

| Type of relays time/current characteristics | *A* | *B* |
|---|---|---|
| Standard-inverse (SI) | 0.14 | 0.02 |
| Very-inverse (VI) | 13.5 | 1 |
| Extremely-inverse (EI) | 80 | 2 |
| Long time standby earth fault | 120 | 1 |

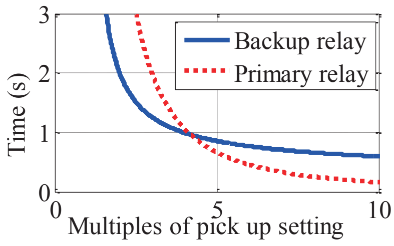

Fig. 3. Standard inverse relay curve for different *TDS* and *Ip*.

standard, is taken as:

$$t = TDS\,(\frac{A}{(\frac{I_F}{Ip})^B - 1}) \tag{1}$$

*TDS* is the time-dial setting and *Ip* is the plug setting; they are adjusted optimally in the conventional coordination strategy. Figure 2(a) shows the standard inverse of the time/current characteristics of relays for different *TDS*. Figure 2(b) shows the same for different *Ip* and *TDS*=0.1. *A* and *B* are constants defined by the name of the curve. For example, for standard inverse *A*=0.14 and *B*=0.02. Other relay curves are given in Table 1, based on the IEC 60255 standard.

As stated earlier, considering different time/current characteristics for relays satisfies the constraints for specified line locations; so the coordination problem is solved for that location. Consequently, by changing the fault location, discrimination time changes and in some cases decreases, which causes miscoordination. To show this problem, a pair of relays that are coordinated by different relay curves is considered in Fig. 3. As can be seen in this figure, these two curves intersect each other--which makes the coordination problem hard. On the other side, fault current does not change linearly along the line, especially for those fed by more than one line. Keeping the above explanation in mind, with inverse curves of the relays, there is no guarantee that constraints along the line will be satisfied for protection coordination, which is solved by user- defined curves for each relay at two or three fault locations. Therefore in this paper, to minimize the number of miscoordinations, we tried to solve the protection problem with the same relay curve for all relays and to find one optimal curve for all relays. In this situation, most pair-relay curve will be parallel, so the probability of infliction is reduced. Therefore, by using this strategy, in addition to reducing the infliction probability, we increase the flexibility of the optimization algorithm to give the optimal setting for achieving minimum overall time of operation of relays during primary and backup operation.

## 2.2 Problem formulation

The aim of the protection coordination problem is to determine what *TDS* and *Ip* is for each relay, and to draw an optimal curve for all relays in order to minimize the overall time of operation of relays during primary and backup operations while maintaining the conditions of protection coordination. Therefore, the objective is defined as needing to minimize the following [24]:

$$Minimize\,T=\sum_{i=1}^{N}\sum_{j=1}^{M}(t_{pij}+\sum t_{bij}) \tag{2}$$

In this equation $t_p$ and $t_b$ identify the operating time of the primary protection relay and the backup protection relay respectively. Considering the A and B constants as continuous variable settings, which are the same for all relays, the relay that identify by $R_j$ will have an operating time $t_j$ as follows:

$$t_j = TDS_j \frac{A}{(\frac{I_{sci}}{Ipj})^B - 1} \tag{3}$$

in which *i* identifies fault location, *M* is total number of relays, and *N* = 2. Considering this strategy, coordination needs to satisfy both the near-end and the far-end fault point.

The objective function is subjected to the optimization process by considering several constraints. The first constraint that must be satisfied is as follows:

$$\Delta t_{pbk} = t_{bk} - t_{pk} - CTI \ge 0 \tag{4}$$

where $\triangle t_{pbk}$ is operating time difference with a coordination time interval between *k-th* relay pairs; and $t_{pk}$ and $t_{bk}$ are the operating times of the primary and backup relays, respectively. This statement is the main running constraint considered in all methods organized for solving the optimized DOCRs coordination problem. In this sentence, *CTI* can take a value between 0.2 and 0.5 seconds [26]. In this study, its value is set as 0.2 sec to assure getting more optimal results. The other technical constraints regarding the relay coordination process are as follows:

$$Ip_{\min} \le Ip_i \le Ip_{\max} \tag{5}$$

$$TDS_{\min} \le TDS_i \le TDS_{\max} \tag{6}$$

$$A_{\min} \le A \le A_{\max} \tag{7}$$

$$B_{\min} \le B \le B_{\max} \tag{8}$$

In constrain (5) $Ip_{\min}$ and $Ip_{\max}$ are determined by the system short-circuit current and the system's rated load current, respectively. *TDS* is considered between 0.1 and 1.1 [24]. Based on the IEC 60255 standard, the maximum and minimum value for *A* are 0.14 and 13.5, respectively. Also based on this standard, the maximum and minimum values for the *B* constant are 0.02 and 1. The last constraint that is considered to assure stability and security

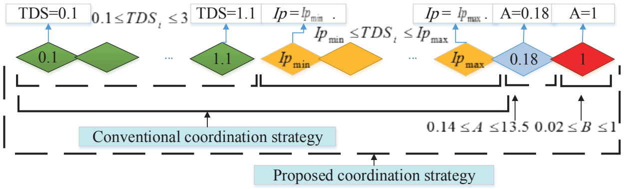

Fig. 4. Structure of chromosomes of proposed coordination strategy.

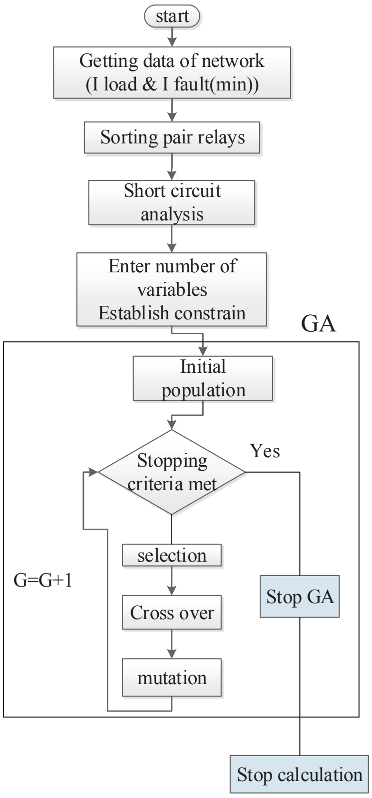

Fig. 5. Flowchart of the proposed optimal approach for DOCRs coordination.

of the protection system is as follows:

$$t_{\min} \le t_{pj} \le t_{\max} \ \forall (t_{\min} = 0.1 \,\&\, t_{\max} = 2.5) \qquad (9)$$

This constraint means that primary relays as main relays must be higher than 0.1 and lower than 2.5. In this paper the optimization problem is solved by a GA algorithm based on the flowchart given in Fig. 4. Also the chromosome structure of this coordination problem is given in Fig. 5.

## 3. SYSTEM AND SIMULATION STEP

The IEEE 30-bus modified test network has been launched as the test-bed. This network is envisaged as a meshed sub-transmission/distribution system. It consists of 30 buses both in 132 and 33 kV, 37 lines, 6 generators, 4 transformers, and 86 DOCRs. The distribution section of the network that will be studied here is shown in Fig. 6. As it ccan be seen, the distribution system connects to the upstream network through three primary distribution substations at buses 1, 6, and 13 (GRID). The generator, transmission lines, and transformers information are is given in [19]. Also in this network, line 18 has pilot protection. Furthermore, two CSG- type DGs are installed at buses 10 and 15. The transient reactance and capacity of the DGs are 0.15p.u. and 10 MVA, respectively. There are two important loads on buses 14 and 3. The relays 13, 30, 37, and 38 are placed near generator buses, which are considered to have protection set with a higher priority and are determined so as to cover 60% of their lines. A total of 38 relays are placed in this network, located on each side of the lines, and represented by R in Fig. 6. The transmission grid is represented by GRID and its data can be found in [26].

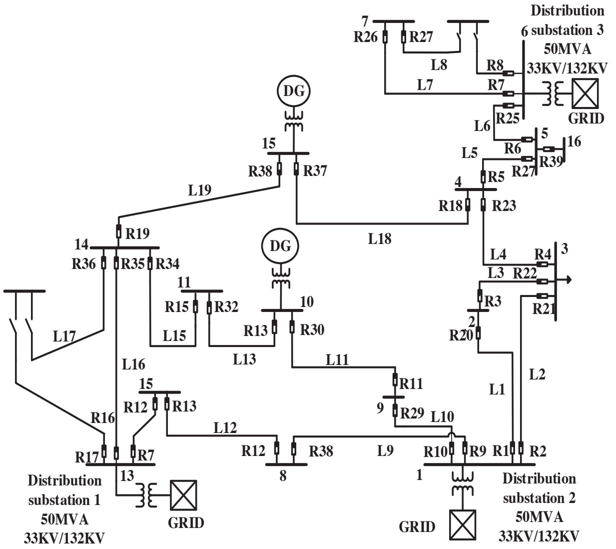

Fig. 6. Test distribution system.

## 4. CONCLUSIONS RESULT AND ANALYSIS

In this section, for comparing the new coordination strategy and the conventional strategy and to validate the performance of the proposed approach, the optimal settings of both coordination strategies are presented for a 30 bus IEEE mesh system which hosts 2 DGs. To show the superiority of the proposed strategy, we present a comprehensive analysis in which the DG capacity and location are varied. In addition, an analysis with different fault resistances is done to validate the proposed strategy. To further test of the proposed coordination strategy, the protection coordination problem solved the near-end and far-end fault points.

### *A. Proposed protection strategy versus conventional strategy*

To evaluate the performance of the proposed coordination strategy, a conventional coordination strategy with two settings (*TDS*, *Ip*) is modeled and solved optimally. The optimal settings of this strategy are given in Table 2 for the near-end fault point. The operation times of relays which are determined by the given optimal setting are shown in Table 4.

The proposed coordination strategy, which was explained previously, is implemented on the same test-study system. As in the conventional strategy, the fault location is considered to be at the near-end fault point. Optimal settings of the proposed strategy are given in Table 3. As can be seen in this table, extra *TDS* and *Ip* optimal curves of relays is given in Table 2. In the conventional strategy, the standard inverse curve is considered to be the relay curve. Therefore $A = 0.14$ and $B = 0.2$. But herein, in the proposed coordination strategy, $A$ and $B$ are determined by GA and equal 2.4673 and 0.5246.

The overall time of operation of relays during primary and backup operation in the new strategy is 41.8233 sec, whereas in the conventional strategy, it is 67.3409 sec. The sum of discrimination

Table 2. Optimal setting of conventional coordination strategy.

| Relay | *TDS* | *IP(p.u.)* | Relay | *TDS* | *IP(p.u.)* | Relay | *TDS* | *IP(p.u.)* | Relay | *TDS* | *IP(p.u.)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.3862 | 552.5095 | 11 | 0.3942 | 288.2855 | 21 | 0.2292 | 216.7833 | 31 | 0.4626 | 200.0448 |
| 2 | 0.4619 | 152.0413 | 12 | 0.5962 | 84.0376 | 22 | 0.4431 | 68.8500 | 32 | 0.6736 | 78.5293 |
| 3 | 0.7106 | 59.0867 | 13 | 0.5214 | 99.8847 | 23 | 0.2454 | 351.2802 | 33 | 0.5332 | 211.8104 |
| 4 | 0.4506 | 247.3429 | 14 | 0.4058 | 153.3978 | 24 | 0.5119 | 115.6064 | 34 | 0.5670 | 205.8639 |
| 5 | 0.3211 | 156.3280 | 15 | 0.3306 | 203.2792 | 25 | 0.4930 | 203.4578 | 35 | 0.2287 | 554.7166 |
| 6 | 0.1637 | 182.6823 | 16 | 0.3420 | 545.9653 | 26 | 0.1000 | 186.9262 | 36 | 0.4105 | 53.3787 |
| 7 | 0.1159 | 241.7884 | 17 | 0.2380 | 236.1211 | 27 | 0.1000 | 87.3210 | 37 | 0.4539 | 67.9493 |
| 8 | 0.1449 | 196.6985 | 18 | 0.5540 | 126.4711 | 28 | 0.2958 | 284.6022 | 38 | 0.4508 | 192.7877 |
| 9 | 0.5563 | 204.7194 | 19 | 0.4810 | 162.5170 | 29 | 0.3390 | 281.7243 | | | |
| 10 | 0.4629 | 320.7466 | 20 | 0.1712 | 428.1231 | 30 | 0.4896 | 177.8565 | | | |

Table 3. Optimal settings of the proposed coordination strategy.

| Relay | *TDS* | *IP(p.u.)* | Relay | *TDS* | *IP(p.u.)* | Relay | *TDS* | *IP(p.u.)* | Relay | *TDS* | *IP(p.u.)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5600 | 552.5095 | 11 | 0.7928 | 288.2855 | 21 | 0.7224 | 1231 | 31 | 0.8482 | 177.8565 |
| 2 | 0.4638 | 152.0413 | 12 | 0.7888 | 84.0376 | 22 | 1.4178 | 216.7833 | 32 | 1.5823 | 200.0448 |
| 3 | 0.2779 | 59.0867 | 13 | 1.8935 | 99.8847 | 23 | 1.2915 | 65.9928 | 33 | 1.0764 | 78.5293 |
| 4 | 1.0848 | 247.3429 | 14 | 0.7355 | 153.3978 | 24 | 0.6661 | 351.2323 | 34 | 1.0888 | 211.8104 |
| 5 | 1.1525 | 156.3280 | 15 | 0.5974 | 203.2792 | 25 | 0.8108 | 115.6064 | 35 | 0.2775 | 205.8639 |
| 6 | 0.2227 | 182.6823 | 16 | 0.2949 | 545.9653 | 26 | 0.1033 | 203.4578 | 36 | 0.6616 | 554.7166 |
| 7 | 0.3047 | 241.7884 | 17 | 0.1965 | 236.1211 | 27 | 0.1452 | 186.9262 | 37 | 1.2004 | 53.3787 |
| 8 | 1.3512 | 196.6985 | 18 | 0.2101 | 126.4711 | 28 | 0.4984 | 87.3210 | 38 | 0.7175 | 67.9493 |
| 9 | 0.4056 | 204.7194 | 19 | 1.4532 | 162.4930 | 29 | 0.4522 | 284.6022 | A | 2.4673 | |
| 10 | 0.8477 | 320.7466 | 20 | 1.1178 | 428. | 30 | 0.8764 | 281.7243 | B | 0.5246 | |
| $\Sigma t_p$=15.9477 sec. | | | | | | | | | | | |

Table 4. Operation time of relays in conventional and proposed approach.

| Relay No. | Conventional strategy | Proposed strategy | Relay No. | Conventional strategy | Proposed strategy | Relay No. | Conventional strategy | Proposed strategy | Relay No. | Conventional strategy | Proposed strategy |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9517 | 0.6577 | 11 | 0.9831 | 0.6647 | 21 | 0.4374 | 0.1705 | 31 | 0.9850 | 0.6291 |
| 2 | 0.7393 | 0.2784 | 12 | 0.9127 | 0.4626 | 22 | 0.6939 | 0.4178 | 32 | 1.0890 | 0.6875 |
| 3 | 1.0604 | 0.5675 | 13 | 0.8649 | 0.5611 | 23 | 0.6945 | 0.4110 | 33 | 0.9416 | 0.5305 |
| 4 | 0.9226 | 0.4484 | 14 | 0.8611 | 0.4466 | 24 | 0.9786 | 0.4959 | 34 | 1.0177 | 0.5642 |
| 5 | 0.4964 | 0.2871 | 15 | 0.7577 | 0.4840 | 25 | 1.1776 | 0.6949 | 35 | 0.7024 | 0.3603 |
| 6 | 0.4314 | 0.2531 | 16 | 0.8683 | 0.4447 | 26 | 0.4040 | 0.1765 | 36 | 0.5206 | 0.1439 |
| 7 | 0.2659 | 0.1145 | 17 | 0.4199 | 0.1336 | 27 | 0.2706 | 0.1053 | 37 | 0.7431 | 0.4088 |
| 8 | 0.2924 | 0.1080 | 18 | 0.9481 | 0.4713 | 28 | 0.9890 | 0.6801 | 38 | 0.9927 | 0.5334 |
| 9 | 0.9959 | 0.6542 | 19 | 0.7727 | 0.5353 | 29 | 0.8611 | 0.5175 | | | |
| 10 | 0.8942 | 0.6618 | 20 | 0.5337 | 0.2744 | 30 | 0.9930 | 0.6355 | | | |

time for the proposed strategy is 5.8337 sec; for the conventional strategy, it is 6.6280 sec.

### *B. Proposed protection strategy considering different size of DG, locations*

To further investigate and test the proposed coordination strategy, several cases have been simulated for different sizes and locations of DGs; these are compared against the conventional coordination strategy. These cases are considered in order to show the superiority of the proposed coordination strategy in reducing the overall time of operation of relays during primary and backup operation. Table 5 summarizes these cases and the overall time of operation in both the proposed and the conventional strategy. To validate the proposed coordination strategy, the optimization problem is solved for near-end and far-end fault points. For brevity, Table 6 gives a sample of primary and backup relay operation times considering the near-end/far-end fault points.

In addition to highlighting the superiority of the proposed coordination strategy, the overall time of operation and various different fault resistances are presented in Table 7, in order to observe clearly the superiority of the proposed coordination strategy. Figure 7 shows the main and backup relay operation time. It worth noting that relays 26 and 27 are not backup for any primary relay; so the, operation time for these relay as a backup relay is zero. Like Fig. 7, which is for near-end faults, Fig. 8 is for far-end fault points. As can be seen in these figures, the overall time of operation of relays during primary and backup operation for different fault locations is reduced.

In the figures, black and red curves are for the proposed coordination strategy, whereas pink and blue curves are for the conventional strategy. In these figures, it is obvious the constraint in equation 13 is fully satisfied, and the black curve, which represents the primary relay's operation time, is under 1 sec, which satisfies constraint 13, that primary relays should operate for less than 2.5 sec. Therefore, it can be concluded that use of the proposed coordination strategy, in which primary relays operate under 1 sec, can assure stability and security of the protection system.

As stated earlier, in this coordination strategy, time/current characteristics of all relays are the same. Therefore, by using the proposed coordination strategy and by solving the optimization problem for the near-end and far-end fault points with no violations, especially miscoordinations, for faults along the line would happen. Therefore using the proposed coordination strategy to gain extra reduction of the overall time of operation of relays during primary and backup operation for different fault locations will suppress miscoordination, thus solving the optimization problem.

Table 5. Comparing proposed and conventional coordination strategies for different sizes and locations of DGs.

| DG size and location | Conventional coordination strategy | | Proposed coordination strategy | | Reduction |
|---|---|---|---|---|---|
| | $\Sigma Topt_m$ | $\Sigma Topt_m+\Sigma Topt_b$ | $\Sigma Topt_m$ | $\Sigma Topt_m+\Sigma Topt_b$ | $\Sigma Topt_m+\Sigma Topt_b$ |
| Without DG | 29.6430 sec | 67.4198 sec | 15.9627 sec | 41.2790 sec | 38.7732% |
| DG @ bus 10 Rated 5 MVA 5 | 28.8495 sec | 68.0106 sec | 16.0403 sec | 41.9137 sec | 38.3718% |
| DG @ bus 10 Rated 10 MVA 4 | 29.5207 sec | 67.9625 sec | 16.3681 sec | 42.0687 sec | 38.1001% |
| DG @ bus 14 Rated 5 MVA 5 | 29.3125 sec | 67.3478 sec | 16.2375 sec | 41.6027 sec | 38.2271% |
| DG @ bus 14 Rated 10 MVA 4 | 28.9637 sec | 67.7390 sec | 15.9856 sec | 42.0820 sec | 37.8763% |
| DG @ bus 10 & 14 Rated 5 MVA 3 | 29.1802 sec | 67.3390 sec | 16.0520 sec | 41.2634 sec | 38.7229% |
| DG @ bus 10 & 14 Rated 5 & 10 MVA respectively 2 | 28.9371 sec | 67.8692 sec | 16.2372 sec | 41.5399 sec | 38.7942% |
| DG @ bus 10 & 14 Rated 10 MVA 1 | 29.4641 sec | 67.3409 sec | 15.9477 sec | 41.8233 sec | 37.8932% |

Table 6. Effect of fault resistance on coordination problem.

| $R_{fault}$(ohm) | Conventional strategy | Proposed strategy |
|---|---|---|
| 0 | 67.3409 s | 41.8233 |
| 0.01 | 67.3445 s | 41.8643 |
| 0.05 | 67.3478 s | 41.8731 |
| 0.1 | 67.3502 s | 41.8954 |
| 0.2 | 67.3554 s | 41.9174 |
| 0.3 | 67.3581 s | 41.94.34 |

Table 7. Sample of relay operation for the near-end/far-end fault points.

| Fault location | Primary | Backup 1 | Backup 2 |
|---|---|---|---|
| @ L18-near end (conventional) | t(4)<br>0.9226 | t(3)<br>1.1226 | t(2)<br>1.1226 |
| @ L18- far end (conventional) | t(4)<br>0.9823 | t(3)<br>1.532 | t(2)<br>1,3652 |
| @ L18- near end (proposed) | t(4)<br>0.4484 | t(3)<br>0.6484 | t(2)<br>0.6484 |
| @ L18- far end (proposed) | t(4)<br>0.5060 | t(3)<br>1.0917 | t(2)<br>0.9917 |

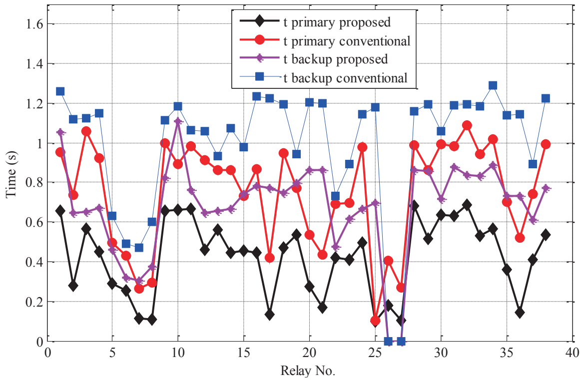

Fig. 7. Comparison between operation time of relays for Near-end fault point.

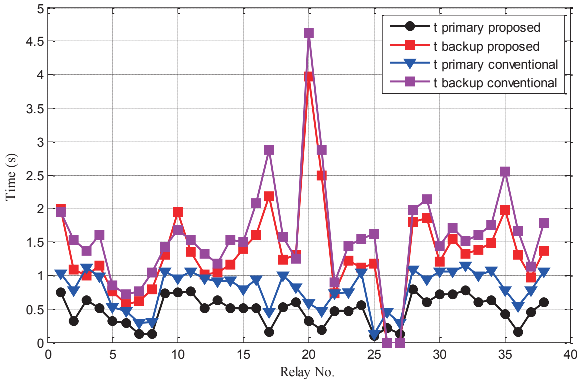

Fig. 8. Comparison between operation time of relays for Far-end fault point.

## 5. CONCLUSION

Coordination of DOCRS is an intricate task in large-scale and interconnected networks, specifically in the presence of DGs. In this paper, a new coordination strategy is established for coordination of DOCRs to achieve a secure protection scheme. The proposed coordination strategy is compared to the conventional one to show the efficiency of the new strategy for finding the optimal settings of relays. In contrast to the conventional coordination strategy, in the proposed strategy an optimal curve is determined for all relays during solution of the coordination problem. Based on digital overcurrent relays, the time/current characteristics can be defined. Various cases are investigated for different sizes of DGs in different locations. At the end, the proposed coordination strategy is tested for the same system with different fault resistances. The results show the superiority of the proposed coordination strategy in reducing the overall time of operation. In this paper, because of using one curve for all relays, the probability of miscoordination is reduced also.

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