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A proposed coordination strategy for meshed distribution systems with DG considering user-defined characteristics of directional inverse time overcurrent relays

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ABSTRACT

In this paper, coordination strategy that considers using user defined characteristics for the inverse time overcurrent relays is proposed. Typically, the coordination between relays operating times within meshed systems are achieved by adjusting two relay settings; pick up current and time multiplier setting (TDS and I_p). The equation that models the digital inverse time overcurrent relay operation has two constants; one of them represents the constant for relay characteristics (A) and the other one represents the inverse time type (B). The proposed coordination strategy considers the two relay characteristics constants as continuous variable settings that can be adjusted. These (A and B) values are chosen optimally in addition to (TDS and I_p) to achieve coordination. The coordination problem is formulated as a nonlinear programming problem where the main objective is to minimize the overall time of operation of relays during primary and backup operation considering faults at different locations. The results are compared against the relay coordination using the conventional settings. The problem is applied to the meshed power distribution network of the IEEE 30 bus systems equipped with synchronous based DGs. The results show that the proposed strategy can significantly reduce the overall relay operating time and thus making it an attractive option for meshed distribution systems with DG.

Introduction

Protection relaying plays a vital role within the operation of any power system. Overcurrent protection is one of the basic protective relaying principles and inverse time overcurrent relays is considered as the backbone of the protection strategies in distribution networks where the overcurrent relays settings are chosen to achieve coordination guaranteeing fast, selective and reliable relay operation to isolate the power system faulted section [1].

Digital microprocessor based overcurrent relays are currently widely used for safe and efficient protection with much more powerful capabilities than conventional electromechanical overcurrent relays [2].

The developments in the relays' technology are essential to cope with the growing interest to develop the traditional electric power grids into "Smart Grid" where an important feature of this smart grid will be the increasing penetration of DG at distribution levels [3]. Generally, integration of DG has different impacts on distribution systems and one major challenge is its effect on the protection system [4]. One basic impact is that addition of DGs will transform the commonly radial distribution networks into meshed and looped structure with bidirectional power flow leading to an increasing dependence on directional inverse time overcurrent relays (DOCRs) in distribution systems. Another DG integration impact on the protection systems is the increase of short circuit levels in the system which depends strongly on the type of DG. In [5], it has been shown that synchronous based DG generates higher fault current levels than inverter based and thus resulting in a much more profound impact on the protection systems while the impact of inverter based DG on the distribution system protection is minimal since inverter based DG fault currents typically range from 1 to 2 per unit. Miscoordination of previously coordinated relays is also an important negative impact for DG addition and generally the new meshed, bidirectional power and dynamic nature of the distribution systems will make achieving relays coordination more difficult [6,7].

The DOCRs become an attractive option for modern distribution systems. Such relays are coordinated optimally to minimize the

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overall time of operation of all relays [8]. To overcome the miscoordination as a result of DG addition, new optimal relay settings need to be determined that take into account its presence. Different optimization methods, including conventional and heuristic techniques have been applied to determine the optimum time dial and pickup current settings of the relays that guarantee coordination and minimum total relay operating times [9–17]. Other protection coordination strategies take advantage of the capabilities of digital DOCRs, to improve the protection system performance especially in presence of DG, either by using different or modified groups of relay settings and characteristics [18–20] or by utilizing the communication potentials in digital relays [21,22].

Most of the literature and research work about coordination consider that all the system relays follow the same time/current characteristics and usually this characteristic is the widely used standard inverse despite that many commercial digital relays give the option of selecting the operating curves between the standard characteristics and some of them provide the option of using user defined curves as can be found in [1,23,24]. In this paper, a coordination strategy for inverse time overcurrent relays that takes in consideration the capability of using user defined curves is proposed. The coordination problem is formulated such that the relay will have four settings: the conventional time dial setting (*TDS*) and pick up current (I_p) in addition to the new two settings *A* and *B* which controls the time/current relation of the relay and the four are optimally chosen. The user will have four optimal values (settings) to be adjusted for each system relay to achieve coordination.

The proposed idea is implemented on directional inverse overcurrent relay (DOCRs) for the protection of the IEEE 30 bus distribution system equipped with synchronous based DGs. The problem is modeled as a non-linear programming problem where the optimal relay four settings are optimally determined. For clarity, through the paper it will be referred to coordination using the two settings *TDS* and I_p as the conventional coordination strategy and to the coordination using the four settings *TDS*, I_p, *A* and *B* as the proposed coordination strategy. Section 'Proposed four settings coordination strategy for directional overcurrent relays' of this paper explains the proposed coordination strategy. Section 'Formulation of the protection coordination problem' shows the optimization problem formulation. Section 'System and simulation setup' presents the test system and the simulation setup. Section 'Results and analysis' gives the detailed results and in Section 'Conclusions', conclusions are drawn.

Proposed four settings coordination strategy for directional overcurrent relays

The typical inverse time current characteristic of a directional overcurrent relay is shown in Fig. 1. In accordance with IEC 60255, this characteristic is formulated by the following equation:

$$t = TDS\frac{A}{\left(\frac{I}{I_p}\right)^{B} - 1} \tag{1}$$

where (*A*) is the constant for relay characteristic, (*B*) is the constant representing inverse time type, (*TDS*) is the relay time dial setting and (I_p) is the pickup current setting. Typically (*A*) and (*B*) can have one of the four fixed standard values shown in Table 1. Different *TDS* values allow working within a range of curves for each relay type characteristics as shown in Fig. 2.

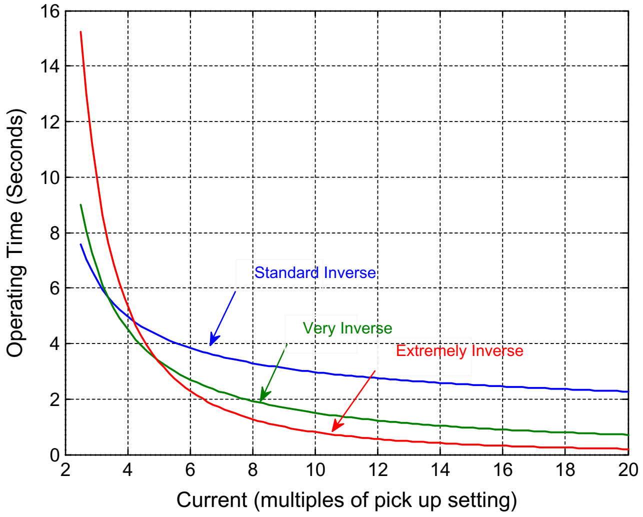

Fig. 1. IEC 60255 inverse time overcurrent relay characteristics at *TDS* = 1.

Table 1
Different types of inverse characteristics curves.

Relay characteristic type	*A*	*B*
Standard inverse	0.14	0.02
Very inverse	13.5	1
Extremely inverse	80	2
Long time standby Earth fault	120	1

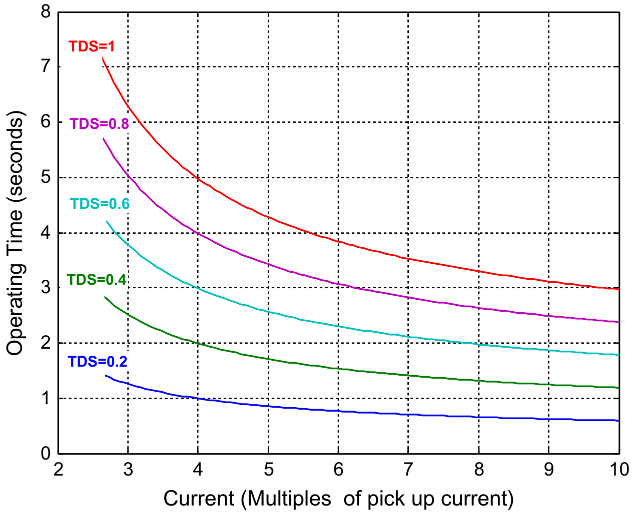

Fig. 2. Typical time/current characteristics of standard inverse time overcurrent relay with different *TDS*.

The proposed approach takes advantage of the flexibility available within digital inverse time overcurrent relays by allowing operating within a wider range of characteristics not limited to the four standard ones. Considering *A* and *B* as variable settings of different values in addition to the conventional *TDS* and I_p allows working within different time–current characteristics.

Formulation of the protection coordination problem

The protection coordination problem can be optimized such that the optimization objective is to minimize the operating times of all the relays while maintaining the conditions of protection coordination. The objective function is taken to be the sum, *T*, of the operating times of all the relays which needs to be minimized as follows:

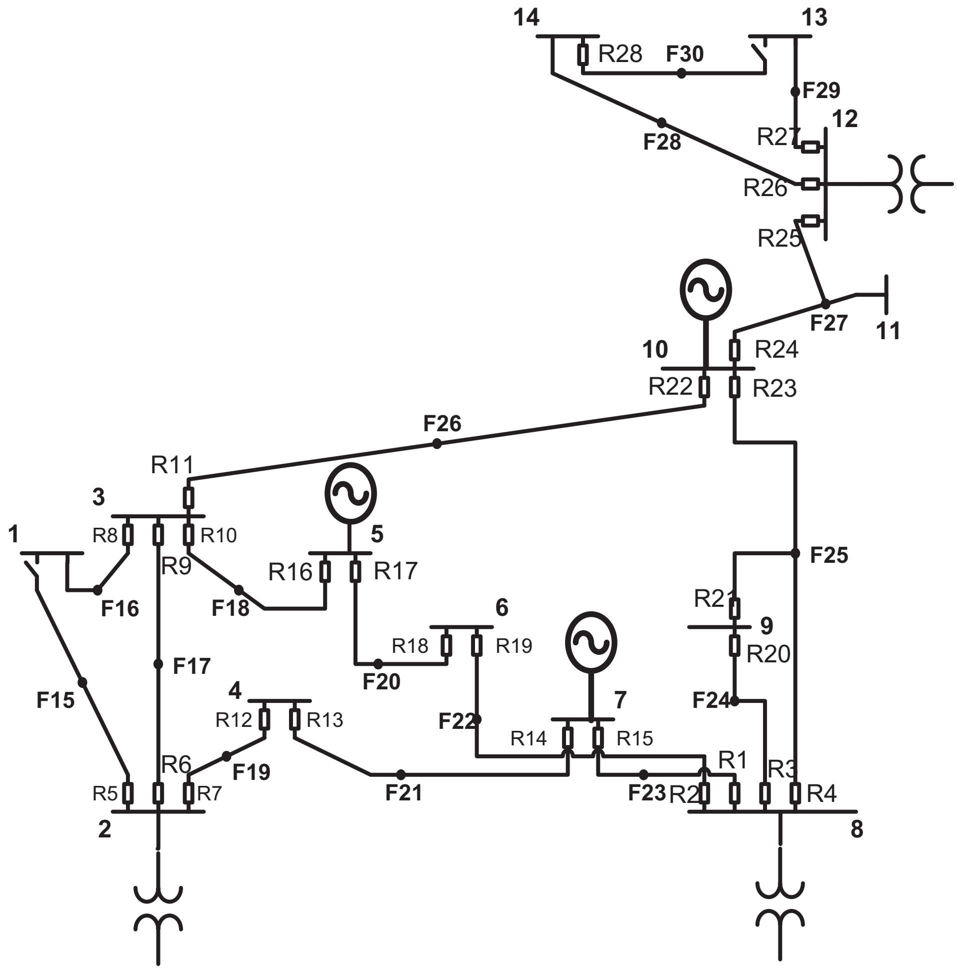

Fig. 3. The distribution portion of the IEEE 30 bus system.

Table 2
Optimal TDS and I_p relays' settings for IEEE 30-bus System-without DG using Conventional Coordination Strategy-.

Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)
1	0.1	0.7479	8	0.1	0.0196	15	0.2921	0.0684	22	0.4019	0.0197
2	0.1	0.5856	9	0.1	0.2219	16	0.2258	0.0605	23	0.3854	0.0627
3	0.1	0.8465	10	0.1	0.5271	17	0.1	0.3326	24	0.1	0.1496
4	0.1	0.1207	11	0.1	0.1699	18	0.1	0.3922	25	0.2226	0.1999
5	0.1	0.0767	12	0.1	0.2228	19	0.1	0.16	26	0.1	0.2111
6	0.1	0.6048	13	0.1	0.4537	20	0.2731	0.0789	27	0.1	0.0622
7	0.1	0.6218	14	0.1	0.4258	21	0.5596	0.0166	28	0.1	0.0367

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

where t_p is the operating time of the primary protection relay and t_b is the operating time of the backup protection relay. Considering the A and B constants as continuous variable settings, the DOCR (j) will have an operating time (t_j) as follows:

$$t_j = TDS_j \frac{A_j}{\left(\frac{I_{sci}}{I_{pj}}\right)^{B_j} - 1} \tag{3}$$

where (i) is the fault location identifier, with the total number of fault locations investigated being N, and (j) is the relay identifier, with the total number of relays being M.

The following constraints must be satisfied while solving the optimized coordination problem:

$$t_{bij} - t_{pij} \geq CTI \ \forall i,j \tag{4}$$

where CTI is the Coordination Time Interval which indicates the minimum time between the primary and the backup relay for a fault next to the primary relay, it usually takes values between 0.2 and 0.5 s. CTI is chosen to be 0.3 s.

For the four settings (TDS, I_p, A, B) relay, it will have maximum and minimum values following the constraints:

$$I_{pmin} \leq I_{pj} \leq I_{Pmax} \tag{5}$$

$$TDS_{jmin} \leq TDS_j \leq TDS_{jmax} \tag{6}$$

$$A_{jmin} \leq A_j \leq A_{jmax} \tag{7}$$

$$B_{jmin} \leq B_j \leq B_{jmax} \tag{8}$$

The minimum and maximum pick up current (I_p) will depend on the system's rated load currents and system's short circuit levels. TDS could take a value between 0.1 and 3 as mentioned in [25,26]. For

Table 3
Primary and backup relays operating times for IEEE 30 bus System-with DG using basic settings.

Fault location	Operating times of relays				*CTI*
	p	b_1	b_2	b_3	
F17	*R6*	*R12*	–	–	0.1394
	0.4563	0.5957	–	–	
	R9	*R16*	*R22*	–	
	0.3543	0.6037	0.741	–	
F19	*R7*	*R9*	–	–	0.0925
	0.4899	0.5824	–	–	
	R12	*R14*	–	–	
	0.3745	0.5826	–	–	
F23	*R1*	*R19*	*R20*	*R21*	0.18
	0.4503	0.6345	0.9842	1.092	
	R15	*R13*	–	–	
	0.6694	0.8683	–	–	
F24	*R3*	*R15*	*R19*	*R21*	0.0877
	0.498	0.7491	0.5857	0.8459	
	R20	*R4*	*R23*	–	0.17
	0.6471	0.8159	0.9082	–	
F25	*R4*	*R15*	*R19*	*R20*	0.036
	0.2881	0.7893	0.6994	0.5743	
	R21	*R3*	*R25*	–	
	0.7807	0.8167	1.1807	–	
	R23	*R11*	–	–	0.1117
	0.8585	0.9702	–	–	

the *A* and *B* constants; it has been chosen to have a minimum value of 0.14 and 0.02 and a maximum value of 1 and 13.5 respectively which represent the standardized values of the IEC 60255 standard for the very inverse time–current relay characteristics. To assure stability and security of the protection system; the primary relay operating time must be between minimum and maximum values of 0.1 and 2.5 s respectively:

$$t_{pmin} \leq t_{pj} \leq t_{Pmax} \tag{9}$$

System and simulation setup

The proposed coordination strategy with the four setting directional overcurrent relays is applied to the distribution portion of the IEEE 30-bus system shown in Fig. 3. The detailed system parameters can be found in [27]. This system is fed through three 50 MVA 132 kV/33 kV transformers connected at buses 2, 8 and 12. Nodes are added at all lines representing fault locations at which three phase short circuit analysis will be carried out.

The proposed strategy has been tested using different case studies including the IEEE 30 bus system without the addition of DG and with the addition of DG considering different DG sizes and locations. It has also been tested considering different fault locations. In [28] the optimization of the protection coordination problem is solved considering midpoint faults and this is one of the cases considered in the analysis but as described in [29], there are three levels of coordination criteria for the faults that should be considered while accomplishing system relay coordination; desired design criteria, minimum criteria and enhanced criteria. The desired criteria is to coordinate considering two classes of faults such as “remote bus faults” (far end faults) and “close bus faults” (near end faults) while “enhanced” criteria will be fulfilled if the coordination considered more classes of faults in addition such as “mid-line” faults. For validating the proposed strategy and for a more accurate coordination study; the “minimum”, “desired” and “enhanced” coordination designs are considered in this paper. Results for the different case studies are reported and analyzed in the following section.

The tested system is constructed and the protection coordination problem is formulated as a nonlinear programming problem using Matlab developed *m*-files and the optimization is solved using built in function *fmincon* (find minimum of constrained nonlinear multivariable function) in the Matlab Optimization Toolbox which relies on the gradient-based method that is designed to work on problems where the objective and constraint functions are both continuous and have continuous first derivatives [30].

Results and analysis

In this section, the optimal relay settings considering both the conventional two settings (*TDS* and I_p) and the additional two proposed settings (*A* and *B*) are presented for the test meshed distribution system considering different configurations with and without DG installation in addition to different coordinating criteria with

Table 4
Optimal TDS and I_p relays’ settings for IEEE 30-bus System-with DG using Conventional Coordination Strategy-.

Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)
1	0.1	0.855	8	0.1	0.0196	15	0.3513	0.0684	22	0.2243	0.0961
2	0.1	0.6811	9	0.1	0.3229	16	0.2773	0.0605	23	0.4176	0.0627
3	0.1	1.0708	10	0.1	0.5952	17	0.1	0.4648	24	0.1	0.1661
4	0.1	0.1395	11	0.1	0.1975	18	0.1	0.4558	25	0.2836	0.1502
5	0.1	0.0768	12	0.1	0.2967	19	0.1	0.2412	26	0.1	0.2174
6	0.1	0.6758	13	0.1	0.538	20	0.2888	0.0789	27	0.1	0.0622
7	0.1	0.7312	14	0.1	0.5503	21	0.5966	0.0166	28	0.1	0.0367

Table 5
Optimal primary and backup relays operating time for IEEE 30-bus System-with DG using Conventional Coordination Strategy.

Fault location	Operating times of relays in sec. (p = primary, b = backup)				
	p	b_1	b_2	b_3	b_4
F15	*R5*	*R9*	*R12*	–	–
	0.1862	0.8136	0.9223	–	–
F16	*R8*	*R6*	*R16*	*R22*	–
	0.1359	0.9274	0.8168	0.8457	–
F17	*R6*	*R12*	–	–	–
	0.4931	0.7931	–	–	–
	R9	*R16*	*R22*	–	–
	0.4411	0.7411	0.7411	–	–
F18	*R10*	*R6*	*R22*	–	–
	0.5380	0.8380	0.8380	–	–
	R16	*R18*	–	–	–
	0.6214	0.9214	–	–	–
F19	*R7*	*R9*	–	–	–
	0.5544	0.8544	–	–	–
	R12	*R14*	–	–	–
	0.4451	0.7451	–	–	–
F20	*R17*	*R10*	–	–	–
	0.5484	0.8484	–	–	–
	R18	*R2*	–	–	–
	0.5816	0.8816	–	–	–
F21	*R13*	*R7*	–	–	–
	0.6839	0.9839	–	–	–
	R14	*R1*	–	–	–
	0.4753	0.7753	–	–	–
F22	*R2*	*R15*	*R20*	*R21*	*R23*
	0.6136	1.3743	1.8241	1.5297	1.5697
	R19	*R17*	–	–	–
	0.4283	0.7283	–	–	–
F23	*R1*	*R19*	*R20*	*R21*	*R23*
	0.4942	1.0210	1.0408	1.1631	1.0793
	R15	*R13*	–	–	–
	0.8053	1.1053	–	–	–
F24	*R3*	*R15*	*R19*	*R21*	*R23*
	0.6011	0.9011	0.9011	0.9011	0.9843
	R20	*R4*	*R23*	–	–
	0.6843	0.9843	0.9843	–	–
F25	*R4*	*R15*	*R19*	*R20*	–
	0.3073	0.9495	1.1985	0.6073	–
	R21	*R3*	*R25*	–	–
	0.8317	1.1317	1.2304	–	–
	R23	*R11*	–	–	–
	0.9304	1.2304	–	–	–
F26	*R11*	*R6*	*R16*	–	–
	0.3166	1.1198	0.9365	–	–
	R22	*R4*	*R21*	*R25*	–
	0.5627	1.0324	1.2515	1.4612	–
F27	*R24*	*R4*	*R11*	*R21*	–
	0.3191	0.8111	0.8724	1.1825	–
	R25	–	–	–	–
	0.8182	–	–	–	–
F28	*R26*	*R24*	–	–	–
	0.3416	0.6416	–	–	–
F29	*R27*	*R24*	–	–	–
	0.1963	0.5460	–	–	–
F30	*R28*	*R26*	–	–	–
	0.2179	0.5179	–	–	–

respect to fault points that include coordinating for midpoint faults only, far-end and near-end faults and far-end, midpoint and near-end faults. Extensive simulations are done with different DG locations and ratings to prove the validity of the proposed coordination strategy. The results of using proposed strategy are compared to using the conventional one.

Simulation results of the conventional and proposed coordination strategy for the test system with DGs and without DGs considering midpoint protection coordination

To evaluate the effectiveness of the proposed coordination strategy, the conventional strategy with the two settings (*TDS* and I_p) and with all the relays in the system following one standardized time/current characteristics are used to protect the distribution portion of the IEEE 30 bus systems. The relays are chosen to be of the standard inverse type with $A = 0.14$ and $B = 0.02$. The protection system is modeled and solved optimally. For testing the system with DG, three synchronous based DGs rated at 5MVA are located at buses 5, 7 and 10.

Table 2 presents the optimal conventional settings TDS and I_p for primary/backup relays for faults at midpoint nodes (F15 to F30) without DG addition using the conventional coordination strategy. All the settings are within the minimum and maximum values formulated within the optimization constraints with a total relay operating time equals 64.1725 s.

When the synchronous based DG units rated 5 MVA are added @ buses 5, 7 and 10, the short circuit currents seen by the relay are changed. If the same settings of the basic system without DGs (in Table 2) are used, this will cause seven cases of miscoordination between primary and backup relays that recorded as shown in Table 3 with a CTI less than 0.2 s. In addition, there are other cases where CTI between the primary/backup pairs are between 0.2 and 0.29 s which do not achieve the chosen optimal constraint in the study but still could be considered coordinated pairs such as R12 and R14 for fault @ F19 and R15 and R13 for fault @ F23. This makes it necessary to calculate new optimal settings for the system with DGs.

Table 4 shows the new optimal settings for the system with DG and Table 5 illustrates the optimal operating time of the primary and backup relays for all fault locations using conventional strategy. The sum of relay operating times (T) using the conventional relay is 63.27 s. All primary and backup relays satisfy the protection coordination constraint by maintaining a minimum coordination time interval of 0.3 s. For example, for a fault at midpoint node F20, each of the primary relays R17 and R18 will have two optimal settings (TDS, I_p) equals 0.1, 0.4648 and 0.1, 0.4558 respectively. These settings will result in an operating time of 0.5484 s for R17 and 0.5816 s for R18 to protect against a fault at node F20. If relay R17 fails to trip, its backup relay R10 will operate after 0.848438 s maintaining a coordination time interval (CTI) of 0.3 s. R2 will act as a backup for relay R18 with an operating time of 0.8816 s keeping the same CTI.

The same protection system is designed using the proposed coordination strategy with the four settings relay with the availability of choosing the time/current characteristics of each system relay. As mentioned previously, this is achieved through considering the A and B constants; which control the characteristics shape; as adjustable settings and optimally choosing them while solving the protection coordination problem. Table 6 shows the new four settings for the different relays for fault locations @ midpoint nodes (F15 to F30). As shown, the primary protection relay R17 will have four settings; two settings for the time dial and pickup current equal 0.1 and 1.1036 respectively, in addition to the settings that indicate its time/current characteristics $A = 0.14$ and $B = 0.331$. Similarly, the settings of R18 will be: $TDS = 0.1$, $I_p = 0.8882$, $A = 0.14$ and $B = 0.2509$. For the backup relays R10 and R2 the settings will be $TDS = 0.1$, $I_p = 1.143$, $A = 0.14$, $B = 0.2073$ and $TDS = 0.1$, $I_p = 1.3265$, $A = 0.14$, $B = 0.284$ respectively. These new curves indicate faster relay operation in response to different fault currents and this results in a total relay operating times = 34.5565 s with a reduction percentage of 45.38% compared to using the conventional overcurrent relay. Table 7 shows the primary/backup relays operating times for fault locations @ midpoint nodes (F15 to F30). For F20 which was previously mentioned as an example, the operating time of relays R17 and R18 hits the minimum with 0.1 s. If the primary protection relays fail to operate, the backup relays R10 and R2 will operate after 0.4 s keeping the $CTI = 0.3$ s.

For the generalization of the usage of the proposed strategy, it has been used within the test system without the addition of DGs. For brevity, Table 8 shows a sample of the primary/backup relay operating times in case no DGs are added to the system while using the proposed four settings coordination. In this case; the overall total operating time records a reduction from 64.1725 s when using the conventional strategy to 35.0626 s using the proposed coordination.

Considering midpoint faults; several case studies have been simulated for DGs @ different locations and with different sizes. The simulation results show the validation of using the proposed coordination strategy while changing the DGs rating and the buses @ which they are installed. Table 9 summarizes the different case studies and the overall relay operating time.

The test cases include installing one DG @ a certain bus (2 or 3 or 6) as well as installing DGs @ different bus (3 and 6) and (3, 6 and 10). The effect of increasing the installed DGs capacities (2 MVA, 4 MVA then 6 MVA @ bus 3) @ bus 3, buses (3 and 6), and buses (3, 6 and 10) for different cases has been also investigated. The proposed coordination is capable of reducing the overall relays operating time in all the simulated case studies.

Simulation results of the conventional and proposed coordination strategy for the test system with DGs considering far/near ends protection coordination

As described in Section ‘System and simulation setup’, there are three levels of coordination criteria for the faults that should be considered while accomplishing system relay coordination; desired design criteria, minimum criteria and enhanced criteria. In the following section; the “desired” and “enhanced” coordination designs are considered and the results are presented.

Table 6
Optimal four relays’ settings for IEEE 30-bus system – with DG using proposed coordination strategy.

Relay	TDS (s)	I_p (p.u.)	A	B	Relay	TDS (s)	I_p (p.u.)	A	B
1	0.1	1.75	0.14	0.1925	15	0.1	0.0684	0.2183	0.02
2	0.1	1.3265	0.14	0.284	16	0.1	0.0605	0.2074	0.02
3	0.1	1.7719	0.382	0.5	17	0.1	1.1036	0.14	0.331
4	0.1	0.2201	0.14	0.074	18	0.1	0.8882	0.14	0.2509
5	0.1	0.1313	0.14	0.0424	19	1.47	0.1795	0.1916	0.5
6	0.14	0.8	1.1174	0.5	20	0.1	0.0789	0.2663	0.02
7	0.1	1.2225	0.14	0.1788	21	0.2545	0.0166	0.1457	0.02
8	0.1	0.0662	0.1402	0.0358	22	0.1	0.0847	7.9413	0.5
9	0.117	0.558	0.5657	0.5	23	0.2556	0.0627	0.1745	0.02
10	0.1	1.143	0.14	0.2073	24	0.5567	0.254	0.3757	0.5
11	0.1	0.2872	0.1807	0.0946	25	0.174	0.0682	13.26	0.5
12	0.1	0.4218	1.447	0.5	26	0.11	0.6479	0.14	0.156
13	0.1	0.938	0.14	0.2865	27	0.1	0.0743	0.14	0.04
14	0.1	1.204	0.14	0.196	28	0.14	0.1911	0.1408	0.1227

Table 7
Optimal primary and backup relays operating time for IEEE 30-bus System – with DG using Proposed Coordination Strategy.

Fault location	Operating times of relays in sec. (*p* = primary, *b* = backup)				
	p	b_1	b_2	b_3	b_4
F15	*R5*	*R9*	*R12*	–	–
	0.1	0.4	0.6507	–	–
F16	*R8*	*R6*	*R16*	*R22*	–
	0.1	0.464	0.44	0.486	–
F17	*R6*	*R12*	–	–	–
	0.1839	0.4839	–	–	–
	R9	*R16*	*R22*	–	–
	0.1	0.4	0.4	–	–
F18	*R10*	*R6*	*R22*	–	–
	0.1	0.4	0.48	–	–
	R16	*R18*	–	–	–
	0.335	0.635	–	–	–
F19	*R7*	*R9*	–	–	–
	0.1	0.4656	–	–	–
	R12	*R14*	–	–	–
	0.1767	0.4767	–	–	–
F20	*R17*	*R10*	–	–	–
	0.1	0.4	–	–	–
	R18	*R2*	–	–	–
	0.1	0.4	–	–	–
F21	*R13*	*R7*	–	–	–
	0.1	0.4	–	–	–
	R14	*R1*	–	–	–
	0.1	0.4	–	–	–
F22	*R2*	*R15*	*R20*	*R21*	*R23*
	0.1	0.61	1.2	0.68	1.197
	R19	*R17*	–	–	–
	0.177	0.477	–	–	–
F23	*R1*	*R19*	*R20*	*R21*	*R23*
	0.1	0.448	0.686	0.516	0.823
	R15	*R13*	–	–	–
	0.357	0.657	–		–
F24	*R3*	*R15*	*R19*	*R21*	*R23*
	0.1	0.4	0.4	0.4	0.751
	R20	*R4*	*R23*	–	–
	0.451	0.751	0.751	–	–
F25	*R4*	*R15*	*R19*	*R20*	–
	0.1	0.4215	0.5125	0.4	–
	R21	*R3*	*R25*	–	–
	0.3691	0.6691	1	–	–
	R23	R11	–	–	–
	0.7096	1	–	–	–
F26	*R11*	*R6*	*R16*	–	–
	0.1	0.615	0.5055	–	–
	R22	*R4*	*R21*	*R25*	–
	0.2556	0.8647	0.5556	1.2125	–
F27	*R24*	*R4*	*R11*	*R21*	–
	0.1532	0.4671	0.4532	0.5249	–
	R25	–	–	–	–
	0.5983	–	–	–	–
F28	*R26*	*R24*	–	–	–
	0.1	0.54	–	–	–
F29	*R27*	*R24*	–	–	–
	0.1	0.4	–	–	–
F30	*R28*	*R26*	–	–	–
	0.1	0.4	–	–	–

The midpoint fault nodes (F15–F30) which were added to the IEEE 30 bus shown in Fig. 3 will be changed by nodes that represent the near and far end faults for the system relays.

Fig. 4 illustrates the concept of the near/far end faults with respect to a certain relay using a simple 2 bus system. For relay R1, the point A' @ distance equals 1% L from relay R1 represents a near end fault point for R1 while A'' @ 99%L is the far end fault point for the same relay R1. Both fault points will have a backup protection from R4 in case R1 fails to trip. At the same time, A' will be the far end fault for R2 and A'' will represent its near end fault with R3 is a backup relay in case it fails to trip.

The protection coordination problem is formulated as an objective function to be minimized subject to different constraints with some additions to suit coordination considering far/near end fault

Table 8
Sample of the Optimal primary and backup relays operating time using Proposed Coordination Strategy for the system without DG.

Fault location	Operating times of relays in sec. (p = primary, b = backup)					Fault location	Operating times of relays in sec. (p = primary, b = backup)				
	p	b_1	b_2	b_3	b_4		p	b_1	b_2	b_3	b_4
F22	*R6*	*R15*	*R20*	*R21*	*R23*	F24	*R3*	*R15*	*R19*	*R21*	*R23*
	0.1	0.73	1.417	0.708	1.277		0.1	0.4	0.4	0.4	0.761
	R19	*R17*	–	–	–		*R20*	*R4*	*R23*	–	–
	0.187	0.487	–	–	–		0.461	0.761	0.761	–	–
F23	*R1*	*R19*	*R20*	*R21*	*R23*	F25	*R4*	*R15*	*R19*	*R20*	–
	0.1	0.447	0.733	0.526	0.841		0.1	0.427	0.5	0.4	–
	R15	*R13*	–	–	–		*R21*	*R3*	*R25*	–	–
	0.35	0.65	–	–	–		0.364	0.664	1.014	–	–
							R23	*R11*	–	–	–
							0.7169	1.016	–	–	–

Table 9
Overall relay operating time (T) considering different DG sizes and locations in case of using conventional and proposed coordination strategies.

DG capacity and location	Conventional coordination strategy	Proposed coordination strategy	DG capacity and location	Conventional coordination strategy	Proposed coordination strategy
DGs rated 2 MVA@ bus 3	64.0842 s	34.9774 s	DGs rated 2 MVA @buses 3,6	64.2495 s	34.9251 s
DGs rated 4 MVA @bus3	64.0014 s	34.8428 s	DGs rated 4 MVA @buses 3,6	64.2374 s	34.8374 s
DGs rated 6 MVA @bus 3	63.9232 s	34.7954 s	DGs rated 6 MVA @buses 3,6	64.2115 s	34.8573 s
DGs rated 2 MVA @ bus6	64.3032 s	35.5473 s	DGs rated 2 MVA @buses 3,6,10	63.581 s	34.5639 s
DGs rated 4 MVA @ bus6	64.4239 s	35.0789 s	DGs rated 4 MVA @buses 3,6,10	63.1246 s	34.3148 s
DGs rated 6 MVA@ bus 6	64.5316 s	35.0992 s	DGs rated 6 MVA @buses 3,6,10	62.7497 s	34.1355 s

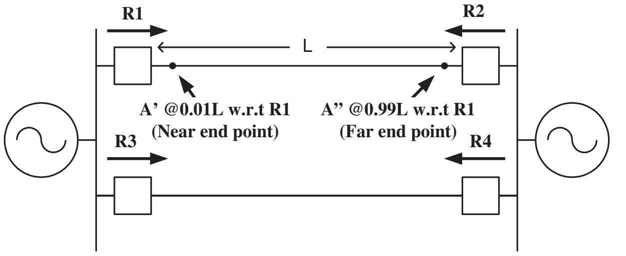

Fig. 4. Near end and far end faults for R1.

points. This includes that the objective function T will represent the overall total operating time of all system relays considering both faults (near and far ends) for each relay as shown in the following equation

$$Minimize\ T = \sum_{j=1}^{M}\left\{\sum_{i=1}^{NR}\left(t_{pij}+\sum t_{bij}\right)+\sum_{i=1}^{FR}\left(t_{pij}+\sum t_{bij}\right)\right\} \qquad (10)$$

Each relay will have to satisfy two constrains considering a $CTI = 0.3$, one for the near end faults and the other for the far end faults.

Both the conventional and the proposed coordination strategy were tested using the same IEEE 30 bus system with DG @ buses 3, 5 and 10 considering near/far ends. Using the conventional two setting directional overcurrent relay with the standard inverse time/current characteristics; the total relay operating time was 256.15 s. Table 10 shows the relay settings (TDS and I_p). Compared to the relay settings in case of coordinating considering midpoint faults where most of the relays operated @ the minimum $TDS = 0.1$;in the new coordination design: 4 relays kept the same settings, 19 relays operate @ higher TDS settings and lower I_p, and 5 relays operate @ higher I_p with the same or lower TDS. Operating at slower time/current characteristics (by increasing the TDS) seems to be the chosen option to achieve the coordination while considering the minimum and the maximum fault current/relay.

For brevity, Table 11 shows a sample of the conventional relay operating times for both faults @ nodes (F15′ and F15″ to F18′ and F18″). When using the proposed four settings coordination with more time/current options which appear due to optimizing the A and B; the total relay operating time was reduced to 142.0453 s. Table 12 shows the optimal four settings (TDS, I_p, A and B) for each relay in the system and Table 13 shows the relay operating time for fault nodes (F15′ and F15″ to F18′ and F18″).

As an example; for the faults @ nodes (F17′ and F17″); F17′ will represent a near end fault for relay R6 with its backup protection relay R12 and a far end fault for relay R9 with its backup relays R16 and R22 while F17″ is the near end fault for R9, R16, R22 and a far end fault for R6 and R12. The operating times of R6 for a near/far ends faults were 0.6447 s and 0.8376 s respectively using the conventional settings coordination as shown in Table 11,

Table 10
Optimal TDS and I_p relays’ settings for IEEE 30-bus System-with DG USING Conventional Coordination Strategy Considering Far/Near Ends Faults.

Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)	Relay	TDS (s)	I_p (p.u.)
1	0.39	0.21	8	0.1	0.0196	15	0.46	0.2312	22	0.44	0.0544
2	0.51	0.093	9	0.24	0.1815	16	0.19	0.2216	23	1.7	0.0627
3	0.1	1.3062	10	0.15	0.5046	17	0.1	0.5695	24	0.31	0.0243
4	0.54	0.2309	11	0.1	0.3433	18	0.43	0.0612	25	0.95	0.1654
5	0.1	0.0768	12	0.28	0.1285	19	0.13	0.3004	26	0.1	0.2624
6	0.28	0.187	13	0.14	0.6935	20	1.17	0.0789	27	0.1	0.0622
7	0.13	0.9173	14	0.2	0.4525	21	1	0.0166	28	0.1	0.0367

Table 11
Sample of the optimal primary and backup relays operating time for IEEE 30-bus System-with DG using Conventional Coordination Strategy Considering Near/Far End Faults.

Fault location	Operating times of relays in sec. (p = primary, b = backup)				Fault location	Operating times of relays in sec. (p = primary, b = backup)			
	p	b_1	b_2	b_3		p	b_1	b_2	b_3
F15′	*R5*	*R9*	*R12*	–	F15″	*R5*	*R9*	*R12*	–
	0.1656	0.9584	0.9473	–		0.2231	2.5	1.45	–
F16′	*R8*	*R6*	*R16*	*R22*	F16″	*R8*	*R6*	*R16*	*R22*
	0.1274	0.8457	0.9449	1.0987		0.1576	1.576	1.5393	1.3696
F17′	*R6*	*R12*	–	–	F17″	*R6*	*R12*	–	–
	0.6447	0.9447	–	–		0.8376	1.4	–	–
	R9	*R16*	*R22*	–		*R9*	*R16*	*R22*	–
	0.9365	1.2365	1.2365	–		0.6415	0.9415	1.0966	–
F18′	*R10*	*R6*	*R22*	–	F18″	*R10*	*R6*	*R22*	–
	0.5433	0.8433	1.0989	–		0.8565	1.1565	1.5898	–
	R16	*R18*	–	–		*R16*	*R18*	–	–
	0.934	1.245	–	–		0.857	0.974	–	–

Table 12
Optimal four relays' settings for IEEE 30-bus system-with DG using proposed coordination strategy considering near/far ends faults.

Relay	TDS (s)	I_p (p.u.)	A	B	Relay	TDS (s)	I_p (p.u.)	A	B
1	2.9	0.068	1.7	0.599	15	1.81	0.068	8.37	1
2	2.15	0.093	0.29	0.182	16	2.99	0.06	1.64	0.784
3	0.1	1.77	0.14	0.134	17	0.1	1.117	0.14	0.23
4	1.53	0.127	6.23	1	18	2.83	0.028	2.4	0.618
5	0.1	0.077	0.14	0.032	19	2.14	0.169	1.02	1
6	2.97	0.181	0.26	0.4395	20	0.61	0.08	0.15	0.02
7	1.15	0.808	0.84	1	21	0.42	0.02	0.14	0.02
8	0.1	0.0196	0.14	0.025	22	2.71	0.02	5.75	0.837
9	1.23	0.181	0.22	0.225	23	0.95	0.06	0.14	0.02
10	0.99	0.851	0.38	1	24	2.75	0.02	0.2	0.204
11	0.11	0.332	0.38	0.215	25	2.99	0.05	11.6	11.63
12	2.99	0.075	2.46	1	26	2.99	0.15	0.76	0.764
13	0.61	0.637	1.38	1	27	0.1	0.06	0.14	0.14
14	2.99	0.404	0.71	1	28	0.1	0.04	0.14	0.14

Table 13
Sample of optimal primary and backup relays operating times for IEEE 30-bus system – with DG using proposed coordination strategy considering near/far ends faults.

Fault location	Operating times of relays in sec. (p = primary, b = backup)				Fault location	Operating times of relays in sec. (p = primary, b = backup)			
	p	b_1	b_2	b_3		p	b_1	b_2	b_3
F15′	*R5*	*R9*	*R12*	–	F15″	*R5*	*R9*	*R12*	–
	0.1	0.5697	0.5823	–		0.1356	1.8529	1.2695	–
F16′	*R8*	*R6*	*R16*	*R22*	F16″	*R8*	*R6*	*R16*	*R22*
	0.1	0.4348	0.6559	0.6639		0.1241	2.2915	1.0876	1.0606
F17′	*R6*	*R12*	–	–	F17″	*R6*	*R12*	–	–
	0.2786	0.5786	–	–		0.4283	1.1923	–	–
	R9	*R16*	*R22*	–		*R9*	*R16*	*R22*	–
	0.5549	0.8889	0.8549	–		0.3529	0.6529	0.6609	–
F18′	*R10*	*R6*	*R22*	–	F18″	*R10*	*R6*	*R22*	–
	0.1328	0.4328	0.6641	–		0.3925	0.6925	1.3473	–
	R16	*R18*	–	–		*R16*	*R18*	–	–
	0.6464	1.0988	–	–		0.4065	0.7065	–	–

and reduced to 0.2786 s and 0.4283 s as shown in Table 13 using the proposed four settings coordination with $A = 0.26$, $B = 0.4395$, $I_p = 0.181$ and $TDS = 2.97$ that results in a faster time/current characteristics. All the other relays operating times for (F17′–F17″) have been also reduced.

Enhanced coordination design – considering far/midpoint/near faults

For enhanced coordination design; a test case that includes coordination based on far/mid/near faults is considered and simulated using both the conventional and the proposed coordination strategy. The objective function to be minimized will be the total relay operating times for faults @ the three fault points subjected to the different pre-discussed constrains. The conventional relay results in a total operating time that equals 337.29 s; and reduced to 200.68 s when using the proposed four settings coordination. For brevity, Table 14 shows the relay operating times for nodes (F17′–F17–F17″) where F17 is added as the midpoint fault. A clear reduction in time can be noticed for the far/mid/near points considering different primary/backup relay pairs when using the proposed coordination strategy compared to the conventional one.

Table 14
Sample of optimal primary and backup relays operating times – using conventional/proposed coordination strategy considering near/mid/far points faults-with DG.

Fault location	Operating times of relays in sec. (*p* = primary, *b* = backup) Conventional Coordination Strategy			Fault location	Operating times of relays in sec. (*p* = primary, *b* = backup) Conventional Coordination Strategy		
	p	b_1	b_2		*p*	b_1	b_2
F17′	*R6*	*R12*	–	F17′	*R6*	*R12*	–
	0.6633	0.9633	–		0.2465	0.5465	–
	R9	*R16*	*R22*		*R9*	*R16*	*R22*
	0.8994	1.1994	1.1994		0.5453	0.8517	0.8453
F17	*R6*	*R12*	–	F17	*R6*	*R12*	–
	0.7427	1.1936	–		0.3235	0.8159	–
	R9	*R16*	*R22*		*R9*	*R16*	R22
	0.7399	1.0456	1.14		0.4082	0.7225	0.7593
F17″	*R6*	*R12*	–	F17″	*R6*	*R12*	–
	0.8593	1.4669	–		0.4463	1.1322	–
	R9	*R16*	*R22*		*R9*	*R16*	*R22*
	0.6161	0.9161	1.0766		0.3048	0.6049	0.6693

Conclusions

This paper proposes a new coordination strategy for the time inverse overcurrent relays in which the user will be capable of defining a relay time/current characteristic that is different from the standard predefined standard curves (standard inverse, very inverse and extremely inverse) and optimally suits the user system's configuration and conditions. That could be achieved by dealing with the *A* and *B* constants that control the shape of the characteristics as adjustable settings in addition to the well-known *TDS* and I_p and thus taking advantage of the wide capabilities available in the digital and numerical relays. The protection coordination problem is formulated as a non linear optimization problem where four optimal settings are determined for each relay. The proposed design is tested on the distribution system portion of the benchmark IEEE-30 bus system. Simulation results show the superiority of the proposed coordination strategy with the four settings inverse time overcurrent relay, in the presence and absence of DG and considering different fault locations in the coordination design, over the conventional well-known relay that has only two adjustable settings. A reduction, in the overall relay operating time, of approximately 50% can be achieved with such new strategy. Furthermore, the results show that the design can achieve reduced relay operating times irrespective of the DG size and, location and irrespective of the number and locations of fault points considered during the coordination design of the system's relays.

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