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Comparative study of optimization methods for optimal coordination of directional overcurrent relays with distributed generators

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ABSTRACT

Due to the growing penetration of distributed generators (DGs), that are based on renewable energy, into the distribution network, it is necessary to address the coordination of directional overcurrent relays (DOCR) in the presence of these generators. This problem has been solved by many metaheuristic optimization techniques to obtain the optimal relay parameters and to have an optimal coordination of the protection relays by considering the coordination constraints. In this article, a comparative study of the optimization techniques proposed in the literature addresses the optimal coordination problem using digital DOCRs with standard properties according to IEC60-255. For this purpose, the three most efficient and robust optimization techniques, which are particle swarm optimization (PSO), genetic algorithm (GA) and differential evolution (DE), are considered. Simulations were performed using MATLAB R2021a by applying the optimization methods to an interconnected 9-bus and 15-bus power distribution systems. The obtained simulation results show that, in case of distributed generation, the best optimization method to solve the relay protection coordination problem is the differential evolution DE.

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1. INTRODUCTION

The main role of protection relays is to detect and eliminate faults as quickly as possible by transmitting an opening command to the related circuit breaker. This circuit breaker isolates the faulty part of the network to ensure that the electrical equipment is not affected by the fault current [1]. The directional overcurrent relay (DOCR) is the most widely used type of relay in the coordination of protection relays due to their simplicity of application and their technical and economic characteristics [2]. The coordination of DOCRs protection has been considered a necessity for distribution networks, as it quickly isolates the faulty area, keeps the system safe and overcomes current faults so that the relays are reliable, flexible and selective [3]. In a properly coordinated system, the main relay must first function on overcurrent faults within a predefined time. After this predetermined time, known as the coordination time interval (CTI), the emergency relay must operate to isolate the default if the main one failed to trip [4]. Relay coordination is usually based on the evaluation of both fault currents and power flow. To optimize relay coordination, two important parameters are considered; relay settings which include the time dial setting (TDS) and the plug setting (PS) [5]. The main objective of relay coordination is to select its optimal parameters, taking into account the limits of these parameters, its characteristic curves and especially the constraints of coordination [6]. Coordination of protection relays can be a complicated problem in interconnected networks because each main relay can have more than one emergency relay and a main relay can also be the emergency relay of another relay, whereas coordination in radial networks is very simple because each relay is an emergency relay of downstream relays [1]. The coordination of DOCRs in an interconnected distribution network is a constrained optimization issue, which reflects the difficulty of this problem.

The Kyoto protocol is an international agreement, which came into force in 2005, for developing countries. It aims to reduce the emission of greenhouse gases, with an emphasis on the increasing use of the renewable energy production [7]. In this regard, the integration of distributed generators (DGs) using renewable energy has become a global concern, given the decreasing costs of power transmission and large power plants construction, the reduction of energy losses, and the decreasing demand for electrical energy on the power grid [8]. Despite its many advantages, these generators have several impacts on electrical network parameters [9], namely the impact on power flow and the modification of fault current values [10] that can affect the operation of electrical network protection schemes. This influence can result in reduced system reliability, increased corrective maintenance costs and poor coordination between existing protective relays in the network [11]. The loss of coordination can lead to unnecessary disconnection of the healthy part of the network, damage to electrical equipment, and larger fault zones [12]. To solve this problem, it is necessary to adjust PS and TDS of the relays considering the existence of the DGs, in order to have a new optimal coordination for the proper operation of the protection of the electrical system.

Many optimization approaches are used to determine the most appropriate coordination of DOCRs, including linear programming (LP), two-phase simplex and double simplex methods, nonlinear programming (NLP) and meta-heuristics. In LP, the PS parameter is assumed to be a fixed value that was calculated using the data of maximum load currents and the fault current, which is why these methods are weakened [4]. Recently, the meta-heuristic methods used in the coordination of protective relays, show faster and more reliable results. These methods include water cycle algorithm (WCA) [4], adaptive modified firefly algorithm (AMFA) [3], improved firefly algorithm (IFA) [2], differential evolution algorithm (DE) [13], symbiotic organism search (SOS) [14], genetic algorithm (GA) [7], particle swarm optimization (PSO) [15], informative differential evolution algorithm (IDE) [16], ant colony optimization (ACO) [17], modified particle swarm optimization (MPSO) [18] and harmony search algorithm (HSA) [19]. A thorough study of the GA, PSO, DE, HSA, and simulated annealing (SA) optimization techniques that are implemented to obtain the best DOCR coordination is presented in [20]. The performance of these methods has been successfully verified for solving this problem.

This article compares optimization methods for determining the optimal parameters of DOCRs with DGs in interconnected distribution networks. The problem has been presented in the second section, the optimization methods PSO, GA and DE are detailed in the third section. The obtained results and discussion are given in the fourth section, and the conclusion is provided in the fifth one.

2. COORDINATION OF DOCRS WITH INTEGRATION OF DGS

This section introduces the coordination problem formulation for relays. Which contains the relay running time, the objective function of this issue, the coordination, reliability. Then the sensitivity constraints that must be met to have optimal coordination, as well as the behavior of DOCRs with DGs.

2.1. Problem formulation

According to IEC60-255, the operating time of the overcurrent relay for standard characteristics is indicated in (1). The running time of the relay is a function of two decision variables, namely TDS and PS, and the fault current I_F [21]. PS is the quotient of the pickup current Ip and the current transformation ratio (CTR), as defined in (2). The minimization of time T, which is the summed running time of all main and emergency relays for each fault location M, represents the DOCR coordination objective function, as expressed in (3), where N is the number of existing relays in the system [22].

$$t = TDS\frac{0.14}{\left(\frac{I_F}{PS}\right)^{0.02} - 1} \tag{1}$$

$$PS = \frac{Ip}{CTR} \tag{2}$$

$$Minimise\ T = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(t_{ij}^{\ \ p} + t_{ij}^{\ \ b}\right) \quad (3)$$

The coordination constraint should be satisfied for all primary/backup relay pairs (P/B). This constraint is indicated in (4). The CTI value depends on the type of relay (digital or electromechanical) and it varies between 0.2 and 0.5 s. The parameters tp and tb are respectively the running time of the main and emergency relays [23]. The reliability constraint is presented in (5), the relay must operate within a time margin, it must respond in a minimum time t_{min} and it must not exceed a maximum time t_{max}, the relay operating time generally varies between 0.1 and 4 s [21].

$$t_b - t_p \geq CTI \quad (4)$$

$$t_{min} \leq t \leq t_{max} \quad (5)$$

The sensitivity constraints are presented in (6) and (7). The parameters TDS and PS must respect the minimum values TDS_{min} and PS_{min} and the maximum values TDS_{max} and PS_{max}. The limits of TDS are generally 0.1 and 1.1 s [24]. The limits of PS are calculated using (8) and (9), where I_{Lmax} is the maximal load current and I_{Fmin} is the minimal fault current [5].

$$TDS_{min} \leq TDS \leq TDS_{max} \quad (6)$$

$$PS_{min} \leq PS \leq PS_{max} \quad (7)$$

$$PS_{min} = max\left\{0.5, \frac{(1.25 \times I_{Lmax})}{CTR}\right\} \quad (8)$$

$$PS_{max} = min\left\{2.5, \frac{\left(\frac{2}{3} \times I_{Fmin}\right)}{CTR}\right\} \quad (9)$$

2.2. DOCRs coordination with DGs

Due to its various advantages, the integration of distributed generators into power grids has become more widespread in the global energy sector, but they also have negative impacts on the distribution network parameters in terms of load current and fault current level, which increases according to the capacity and location of DGs relative to the fault [10], [25]. Therefore, power grid protection systems may be affected. The type of DG and the characteristics of the distribution network have a significant effect on the coordination of the protection [11]. The consequences related to the connection of distributed generators to the network are nuisance tripping, blinding of protections and loss of coordination of the protection relays. This can lead to a decrease in system reliability and an increase in corrective maintenance costs [26]. Therefore, it is necessary to optimize the DOCRs protection relay parameters according to the new system configuration.

3. OPTIMIZATION METHODS FOR THE OPTIMAL DOCRs COORDINATION

This section presents the three most efficient and robust optimization methods used to solving DOCRs coordination, which are PSO, GA and DE. These algorithms have a randomly generalized initial population, in order to obtain the best solution by reaching the optimal point in the search space. x is the variable vector presented in (10); D is the dimensions of each element of the population, which is the number of variables and N is the population size.

$$x = \{x_1;\ x_2;\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots;\ x_D\} \quad (10)$$

3.1. Particle swarm optimization

Particle swarm optimization is an optimization approach based on the social behavior of birds and school fish, combined with the swarm intelligence. Individuals can perform extremely complex tasks when interacting with each other because each individual has little or no wisdom [20]. Each particle is initialized randomly with its velocity vj and its position xj. At each step, each particle moves in the D-dimensional search space according to three criteria: its best score (Pbset), the best score of all particles (Gbest) and random factors rand1 and rand2. In (11) and (12) are used to actualize the velocity and position of particles at each iteration k. Where c_1 is the personal learning coefficient, c_2 is the global learning coefficient and w is the inertia weight.

$$v_j^{k+1} = w \times v_j^k + c_1 \times rand_1(\ \ ) \times \left(Pbest_j{}^k - x_j{}^k\right) + c_2 \times rand_2() \times (Gbest^k - x_j{}^k) \quad (11)$$

$$x_j^{k+1} = x_j{}^k + v_j{}^{k+1} \quad (12)$$

3.2. Genetic algorithm

Darwin's natural selection theory was based on the GA to find optimal solutions that should be best suited to the objective function of the problem taking into account the constraints. At each iteration, the genes of each individual, which are the decision variables, undergo genetic operations (selection, crossover, mutation, and elitism) to generate new individuals better at solving the problem. In this algorithm, the individual is estimated and receives a score referring to its competence to execute the objective function and the constraints. The selection process consists in choosing in the middle of the randomly generated population a series of individuals, this process is totally random and does not favour choice within the population. In the crossing process, the two best individuals obtained during the selection process will be chosen as parents. The fundamental role of the crossover process is the exchanging of genetic information in order to increase the genetic variety between the population individuals. The process of mutation inserts diversity in the population, it allows the creation of new genetic traits that are not present in any previous generation individual, which ensures the best research in the resolution space of the system. The crossover factor (CF) represents the probabilities that pairs of chromosomes will produce offspring and the mutation factor (MF) represents the probabilities of a change in status of a chromosome [7].

3.3. Differential evolution

The DE algorithm represents a simple and efficient evolutionary algorithm based on natural gene selection. The DE algorithm has been shown to be faster than other evolutionary algorithms since it involves less mathematical operations and execution time [13]. An initial population is first randomly generated. For each population element, a mutant vector is created using the (13),

$$TX_{i,j} = x_{a_1,j}{}^k + F \times (x_{a_2,j}{}^k - x_{a_3,j}{}^k) \quad (13)$$

with a_1, a_2 and $a_3 \in \{1, 2,\dots, N\}$ are three mutually different random indices and F is the mutation factor that regulates the differential variation amplification $(x_{a_2,j}{}^k - x_{a_3,j}{}^k)$. A crossover is inserted to increase the variety of perturbed parameter vectors to obtain the test vector. Crossover execution on the test solution is performed using the crossover rate (CR) and the random index randk where randk equals randi(D), as expressed in (14) [27], the Selection of the trial solution is made using system at (15), with TFi is the trial fitness.

$$U_{i,j} = \begin{cases} TX_{i,j}\, if\ rand() \leq\ CR\ or\ \mathrm{j}{=}randk \\ X_{i,j}{}^k if\ rand() >\ CR\ and\ j \neq randk \end{cases} \quad (14)$$

$$X_{i,j}{}^{k+1} = \begin{cases} U_{i,j} \forall j\ if \quad TF_i\ <\ F_i^k \\ X_{i,j}{}^k \forall j\ if \quad TF_i\ \geq\ F_i^k \end{cases} \quad (15)$$

4. RESULTS AND DISCUSION

To ensure coordination of DOCRs in distribution networks with integrated DGs, the optimization methods described in the previous section are applied to interconnected 9-bus and 15-bus distribution systems with digital protection relays and standard characteristics. The PS limits are calculated using (8) and (9), the TDS boundaries are 0.1 and 1.1 s and The CTI value for both networks is 0.2 s. The relay operating time limits are 0.1 and 4 s.

4.1. Distribution system 9 bus

Figure 1 shows a 9-bus distribution network supplied by 100 MVA, 33 kV containing four DGs. Each DG is designed with nominal values of 8 MVA. This system contains 12 lines with the same impedance and 24 protection relays (R_1, R_2, . . ., R_{24}). They have 44 pairs of P/B relays between them. The CTR is 500/1 for all relays.

Table 1 gives the optimal adjustments of the 24 protection relays, which are PS and TDS, obtained by PSO, GA and DE optimization methods, while Table 2 shows the values for the running time of the main and the emergency relays t_p and t_b, as well as the coordination time interval corresponding to 44 P/B relay combinations for this optimization approach. The last two rows of Table 1 show the objective function (OF) and the time of convergence for each method. The objective function is the total of the running times of all main and emergency relays with the obtained optimal settings. The CTI between the main and emergency relay running times of the 44 pairs of P/B relays for the different methods is illustrated in Figure 2.

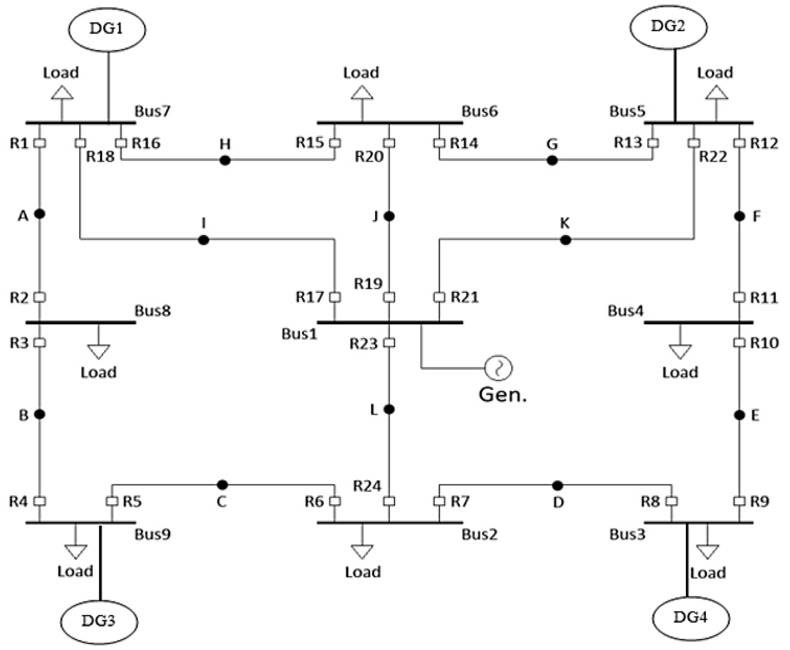

Figure 1. Diagram of a 9-bus interconnected distribution system

Table 1. Optimal relay settings obtained for 9-bus distribution network

Relay N°	PSO		GA		DE	
	TDS	PS	TDS	PS	TDS	PS
1	0.1640	0.5004	0.1469	0.9516	0.1011	0.9583
2	0.1690	0.6611	0.2295	0.5319	0.1767	0.5474
3	0.1597	0.6893	0.2835	0.5181	0.1122	1.1865
4	0.1757	0.7347	0.2908	0.5	0.2170	0.5021
5	0.1280	0.6597	0.2573	0.5004	0.1449	0.5028
6	0.1	1.0390	0.2280	0.5412	0.1120	0.9894
7	0.1149	0.9031	0.2612	0.5079	0.1	1.1016
8	0.1422	0.5065	0.2164	0.5	0.1547	0.5148
9	0.1626	0.8248	0.2962	0.5014	0.1930	0.6447
10	0.1254	0.9628	0.2548	0.5	0.2013	0.5156
11	0.1833	0.5729	0.21032	0.5012	0.1874	0.5226
12	0.2657	0.5	0.2208	0.5	0.1277	1.0438
13	0.1327	0.8484	0.2014	0.5046	0.1587	0.5261
14	0.2144	0.6968	0.2297	0.5	0.1918	0.5085
15	0.1628	0.5006	0.1760	0.5196	0.1348	0.5595
16	0.1713	0.7169	0.1940	0.5016	0.1690	0.5123
17	0.1	1.3394	0.1389	1.1898	0.1076	1.1521
18	0.1	1.1033	0.1280	1.1172	0.1002	1.1624
19	0.1078	1.1414	0.1402	1.0282	0.1161	1.0280
20	0.1	1.3067	0.1313	1.0457	0.1	1.0492
21	0.1424	1.2134	0.1349	1.1260	0.1011	1.4070
22	0.1	1.1033	0.1069	1.1138	0.1	1.1203
23	0.1	1.2679	0.1304	1.2663	0.1024	1.2671
24	0.1009	1.2663	0.1004	1.2842	0.1003	1.2689
OF	45.9697		52.7033		41.9191	
Convergence time (s)	151.990042		84.607213		29.746952	

Table 2. CTI values and running times of primary and emergency relays for a 9-bus distribution network

	Relay pairs R_p/ R_B	PSO			GA			DE		
		t_p	t_b	CTI	t_p	t_b	CTI	t_p	t_b	CTI
1	1/15	0.3582	0.5582	0.2	0.4072	0.6150	0.2077	0.2809	0.4898	0.2089
2	1/17	0.3582	0.6812	0.3230	0.4072	0.8461	0.4388	0.2809	0.6372	0.3563
3	2/4	0.6047	0.8057	0.2010	0.7356	1.0580	0.3224	0.5739	0.7912	0.2173
4	3/1	0.4753	0.6755	0.2001	0.7485	0.9895	0.2410	0.4397	0.6853	0.2456
5	4/6	0.5491	0.7501	0.2010	0.7702	0.9962	0.2260	0.5757	0.7976	0.2220
6	5/3	0.4379	0.6437	0.2058	0.7712	0.9764	0.2052	0.4353	0.6669	0.2317
7	6/8	0.2992	0.5012	0.2020	0.5273	0.7574	0.2300	0.3280	0.5498	0.2218
8	6/23	0.2992	0.6724	0.3732	0.5273	0.8760	0.3487	0.3280	0.6882	0.3602
9	7/5	0.3235	0.5235	0.2	0.5910	0.9010	0.3100	0.3075	0.5087	0.2012
10	7/23	0.3235	0.6724	0.3489	0.5910	0.8760	0.2851	0.3075	0.6882	0.3807
11	8/10	0.4286	0.6305	0.2020	0.6482	0.8614	0.2131	0.4695	0.6911	0.2216
12	9/7	0.5373	0.7373	0.2	0.7853	1.0867	0.3014	0.5686	0.7886	0.220
13	10/12	0.4383	1.0937	0.6554	0.6632	0.9086	0.2454	0.5303	0.9454	0.4151
14	11/9	0.6091	0.8091	0.2	0.6555	1.0792	0.4236	0.5956	0.8135	0.2179
15	12/14	0.6834	0.8834	0.2	0.5677	0.7868	0.2190	0.4579	0.6626	0.2047
16	12/21	0.6834	0.8834	0.2	0.5677	0.7837	0.2159	0.4579	0.7236	0.2656
17	13/11	0.3875	0.6480	0.2	0.4787	0.6948	0.2161	0.3828	0.6320	0.2491
18	13/21	0.3875	0.8273	0.2605	0.4787	0.7368	0.2581	0.3828	0.6712	0.2883
19	14/16	0.5524	0.8160	0.4397	0.5240	0.7387	0.2147	0.4401	0.6513	0.2112
20	14/19	0.5524	0.7600	0.2636	0.5240	0.8924	0.3684	0.4401	0.7391	0.2990
21	15/13	0.3717	0.5717	0.2076	0.4070	0.6514	0.2444	0.3200	0.5236	0.2037
22	15/19	0.3717	0.5717	0.2	0.4070	0.6875	0.2805	0.3200	0.5694	0.2494
23	16/2	0.4657	0.6657	0.2	0.4601	0.8018	0.3417	0.4039	0.6263	0.2224
24	16/17	0.4657	0.6657	0.2	0.4601	0.8288	0.3687	0.4039	0.6245	0.2206
25	17/20	0.2697	0.6712	0.4015	0.3572	0.7226	0.3653	0.2733	0.5519	0.2785
26	17/22	0.2697	0.5752	0.3056	0.3572	0.6199	0.2626	0.2733	0.5828	0.3094
27	17/24	0.2697	0.6569	0.3872	0.3572	0.6623	0.3051	0.2733	0.6537	0.3803
28	18/2	0.4068	1.4872	1.0804	0.5244	1.5791	1.0548	0.4206	1.2511	0.8305
29	18/15	0.4068	1.0564	0.6497	0.5244	1.1834	0.6591	0.4206	0.9772	0.5566
30	19/18	0.2751	0.5429	0.2678	0.3439	0.7016	0.3577	0.2849	0.5673	0.2825
31	19/22	0.2751	0.5425	0.2673	0.3439	0.5843	0.2404	0.2849	0.5491	0.2643
32	19/24	0.2751	0.6150	0.3399	0.3439	0.6195	0.2756	0.2849	0.6119	0.3270
33	20/13	0.4207	1.6686	1.2480	0.4846	1.2995	0.8149	0.3699	1.0655	0.6957
34	20/16	0.4207	1.6483	1.2276	0.4846	1.2446	0.7600	0.3699	1.1062	0.7363
35	21/18	0.3693	0.5757	0.2065	0.3399	0.7445	0.4046	0.2780	0.6031	0.3251
36	21/20	0.3693	0.6712	0.3019	0.3399	0.7226	0.3827	0.2780	0.5519	0.2739
37	21/24	0.3693	0.6569	0.2876	0.3399	0.6623	0.3225	0.2780	0.6537	0.3757
38	22/11	0.4065	1.3627	0.9562	0.4370	1.3657	0.9288	0.4102	1.2669	0.8567
39	22/14	0.4065	2.0219	1.6154	0.4370	1.4882	1.0512	0.4102	1.2626	0.8524
40	23/18	0.2601	0.5307	0.2706	0.3391	0.6857	0.3466	0.2663	0.5541	0.2878
41	23/20	0.2601	0.6110	0.3509	0.3391	0.6683	0.3292	0.2663	0.5103	0.2440
42	23/22	0.2601	0.5303	0.2702	0.3391	0.5711	0.2320	0.2663	0.5367	0.2704
43	24/5	0.5238	1.1155	0.5918	0.5267	1.6596	1.1330	0.5210	0.9389	0.4179
44	24/8	0.5238	0.9281	0.4043	0.5267	1.3947	0.8681	0.5210	1.0252	0.5042

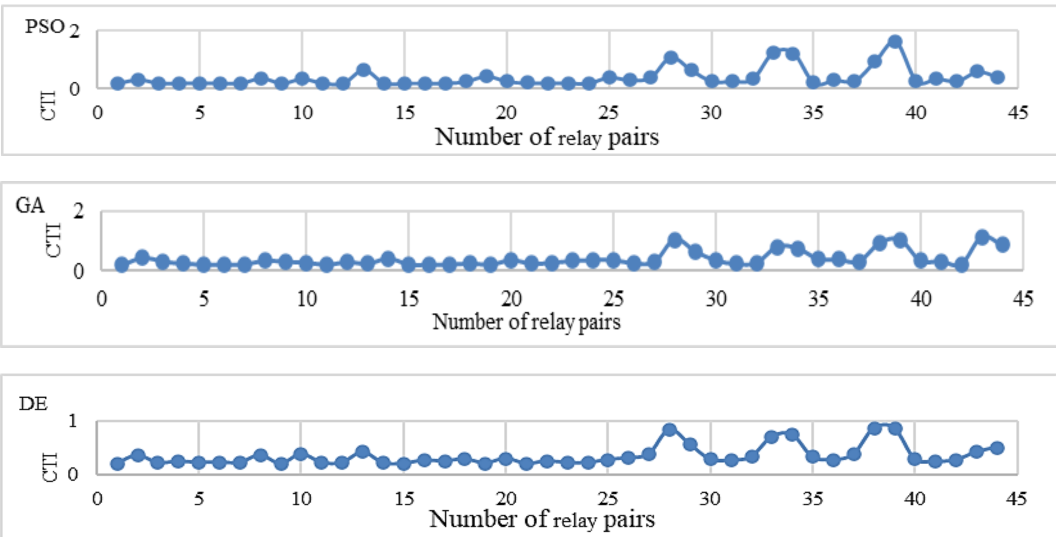

Figure 2. CTI calculated by different algorithms for a 9-bus distribution network

From Table 1, it is clear that the three methods give optimal values of TDS and PS that respect the sensitivity constraint. However, it is observed that the optimization method DE has the lowest values of the OF and the convergence time compared to the other methods. And from Table 2, it is noticed that the reliability constraint is well verified since the operating time is within the limits indicated as well as the coordination constraint is respected for the 44 pairs of P/B relays. It is also noticed from this table that the values of CTI for the DE method are the smallest values compared to the other methods. Similarly, from Figure 2, it can be seen that the values of CTI found by DE belong to the interval [0,1] whereas the values of CTI of the methods PSO and GA belong to the interval [0,2], which explains why the method DE gives the best result compared to the two other methods.

4.2. Distribution system 15 bus

The 15-bus interconnected distribution system presents an example of a high DG penetration distribution system. Six 15 MVA generators with 15% synchronous reactance are connected to buses 1, 3, 4, 6, 13 and 15. Therefore, this system is composed of 42 directional overcurrent relays and 82 pairs of main/emergency relays with 84 decision variables including 42 variables for TDS and 42 variables for PS. More details about this system are provided in [28], [29]. This information contains the fault current values, the current transformation ratio of the relays as well as the P/B pairs of relays.

Tables 3 and 4 show respectively the optimal relay setting of the 42 protection relays, the primary relay running time t_p and the emergency relay running time t_b as well as the CTI values corresponding to 82 P/B relay combinations, for the the proposed optimization methods. Figure 3 illustrates the plot of the CTI values. The last two rows of Table 3 show the objective function and convergence time for each method. It is observed from Table 3 that the methods applied to this network give optimal results that respect the sensitivity constraint given that the TDS and PS parameters are within the previously mentioned limits. However, it is also observed that the value of OF is the smallest for DE compared to PSO and GA as well as the convergence time is shorter for this method. From Table 4, it can be seen that the running times of all main and emergency relays are greater than 0.1 s and less than 4 s and the coordination constraint is greater than or equal to 0.2 s for all primary and emergency relay combinations for the studied methods, which means that the reliability and coordination constraints are well respected. Table 4 and Figure 3 show that the CTI values for DE have the smallest values, for the 44 P/B relay pairs, compared to the other two methods. In Figure 3, it can also be observed that the CTI values obtained by DE vary between 0 and 1, while the CTI values of PSO and GA methods belong to the interval [0,2], then it can be concluded that the best optimization technique for solving the relay protection coordination problem is differential evolution DE.

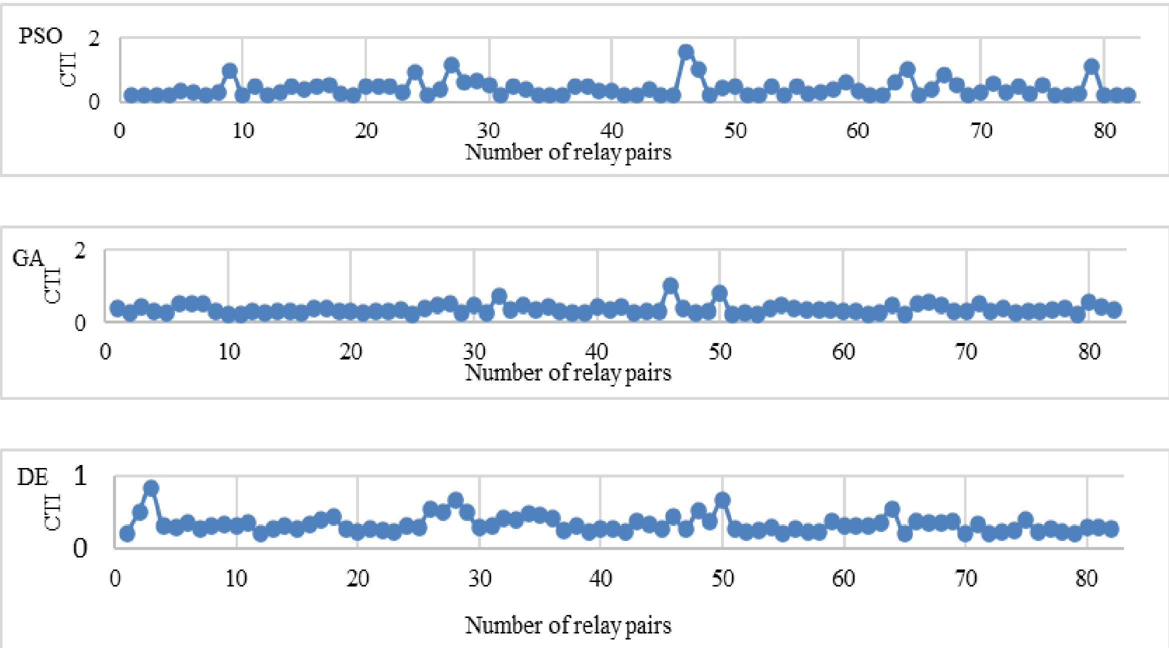

Figure 3. CTI obtained by different methods for15-bus distribution network

Table 3. Optimal relay settings obtained for 15-bus distribution network

Relay N°	PSO		GA		DE	
	TDS	PS	TDS	PS	TDS	PS
1	0.1927	1.8315	0.3898	0.5022	0.3872	0.5033
2	0.5408	0.5003	0.2380	1.1806	0.1295	2.1692
3	0.3103	0.9281	0.2869	1.0676	0.3501	0.5180
4	0.2959	0.7051	0.1529	1.1005	0.2742	0.5
5	0.1956	1.731	0.3908	0.5009	0.2571	1.0105
6	0.2824	0.5	0.3858	0.5946	0.2871	0.7981
7	0.3543	0.9234	0.3339	0.9176	0.3038	1.1323
8	0.1924	0.7828	0.3170	0.5025	0.2140	0.9936
9	0.2483	0.9330	0.3164	0.8852	0.3298	0.5060
10	0.2549	1.3245	0.3754	0.5084	0.3768	0.5099
11	0.2252	0.6843	0.3120	0.52402	0.3031	0.5488
12	0.2387	0.8271	0.3225	0.5148	0.1893	1.1826
13	0.2055	1.6410	0.3852	0.5263	0.1962	1.3537
14	0.1732	1.0571	0.3167	0.5093	0.1420	1.6141
15	0.2605	0.5889	0.2832	0.6766	0.1789	0.8464
16	0.3853	0.8544	0.4094	0.5097	0.2027	2.4877
17	0.2615	2.2424	0.4479	0.5133	0.2398	2.4995
18	0.2989	0.5308	0.2752	0.5060	0.2031	0.5583
19	0.2448	0.8197	0.3655	0.5492	0.3402	0.5061
20	0.2041	1.0261	0.1624	1.3124	0.2685	0.5148
21	0.2656	0.8212	0.3586	0.5062	0.28752	0.5353
22	0.2647	1.3518	0.4133	0.5	0.4055	0.5663
23	0.2884	1.0653	0.4192	0.5009	0.2858	0.5012
24	0.6646	0.5454	0.3353	1.1196	0.2718	1.1967
25	0.3427	0.9108	0.4763	0.5013	0.2543	1.0744
26	0.3431	0.6694	0.3792	0.5128	0.2787	0.9207
27	0.3167	1.0306	0.3894	0.5046	0.1838	1.7407
28	0.3554	0.5	0.2998	1.1362	0.3333	0.6306
29	0.2211	0.8242	0.2955	0.5315	0.2420	0.5585
30	0.2916	1.0476	0.4513	0.5697	0.3884	0.5418
31	0.4326	1.1043	0.3517	1.2376	0.3897	0.6185
32	0.3863	1.1638	0.4378	0.5607	0.4478	0.5044
33	0.4334	1.1040	0.5137	0.5061	0.2545	1.3557
34	0.3121	2.1595	0.4075	0.6290	0.3625	0.6644
35	0.2015	2.0121	0.4292	0.5	0.3486	0.5075
36	0.2693	1.1582	0.4165	0.5112	0.2870	0.5397
37	0.2614	0.9556	0.2434	1.3877	0.2770	0.5531
38	0.3865	1.4028	0.5288	0.5025	0.4567	0.5080
39	0.2973	1.2232	0.3269	1.1476	0.1814	2.1229
40	0.2258	1.6106	0.4641	0.5081	0.3811	0.5674
41	0.6453	1.3827	0.5337	0.5875	0.4952	0.5005
42	0.3100	1.0622	0.2753	1.0453	0.1832	1.5253
OF	117.8449		115.1764		100.6638	
Convergence time (s)	202.854672		178.830934		45.534464	

Table 4. CTI values and running times of primary and emergency relays for a 15-bus distribution network *(Continue…)*

Relay pairs R_p/ R_B		PSO			GA			DE		
		t_p	t_b	CTI	t_p	t_b	CTI	t_p	t_b	CTI
1	1/6	0.5230	0.7251	0.2020	0.6896	1.0616	0.3719	0.6854	0.8992	0.2138
2	2/4	1.0011	1.2013	0.2002	0.5813	0.8453	0.2640	0.4072	0.9223	0.5151
3	2/16	1.0011	1.2011	0.2	0.5813	1.0278	0.4465	0.4072	1.2442	0.8370
4	3/1	0.6388	0.8396	0.20098	0.6177	0.9222	0.3045	0.6086	0.9167	0.3081
5	3/13	0.6388	0.9983	0.3595	0.6177	0.8820	0.2643	0.6086	0.8941	0.2855
6	4/7	0.6161	0.9330	0.3169	0.3703	0.8772	0.5068	0.5146	0.8703	0.3557
7	4/12	0.6161	0.8161	0.2	0.3703	0.8875	0.5172	0.5146	0.7900	0.2754
8	4/20	0.6161	0.9359	0.3198	0.3703	0.8926	0.5223	0.5146	0.8381	0.3235
9	5/2	0.5376	1.5050	0.9674	0.7076	1.0275	0.3199	0.5777	0.9094	0.3317
10	6/8	0.5025	0.7025	0.2	0.7206	0.9325	0.2119	0.5857	0.8967	0.3110
11	6/10	0.5025	0.9956	0.4931	0.7206	0.9406	0.2120	0.5857	0.9450	0.3593
12	7/5	0.7717	0.9717	0.2	0.7257	1.0133	0.2875	0.7096	0.9157	0.2061
13	7/10	0.7717	1.0593	0.2876	0.7257	0.9791	0.2533	0.7096	0.9838	0.2742
14	8/3	0.4051	0.9050	0.4998	0.5841	0.8911	0.3070	0.4878	0.8129	0.3251
15	8/12	0.4051	0.7971	0.3919	0.5841	0.8706	0.2865	0.4878	0.7678	0.2801
16	8/20	0.4051	0.9072	0.5020	0.5841	0.8601	0.2760	0.4878	0.8201	0.3324
17	9/5	0.5145	1.0450	0.5306	0.6448	1.0528	0.4080	0.5721	0.9648	0.3927
18	9/8	0.5145	0.7878	0.2734	0.6448	1.0226	0.3778	0.5721	1.0234	0.4513
19	10/14	0.6143	0.8143	0.2	0.6690	0.9868	0.3178	0.6720	0.9424	0.2704

Table 4. CTI values and running times of primary and emergency relays for a 15-bus distribution network

Relay pairs R_p/ R_B		PSO			GA			DE		
		t_p	t_b	CTI	t_p	t_b	CTI	t_p	t_b	CTI
20	11/3	0.4659	0.9244	0.4586	0.5951	0.9115	0.3164	0.5861	0.8269	0.2409
21	11/7	0.4659	0.9335	0.4677	0.5951	0.8776	0.2826	0.5861	0.8708	0.2848
22	11/20	0.4659	0.9368	0.4709	0.5951	0.8936	0.2985	0.5861	0.8386	0.2526
23	12/13	0.5312	0.8231	0.2919	0.6181	0.9177	0.2995	0.4788	0.7052	0.2264
24	12/24	0.5312	1.4513	0.9200	0.6181	0.9596	0.3414	0.4788	0.8007	0.3219
25	13/9	0.5473	0.7582	0.2109	0.7023	0.9435	0.2412	0.4850	0.7863	0.3013
26	14/11	0.4062	0.7856	0.3795	0.5889	0.9557	0.3668	0.3916	0.9485	0.5569
27	14/24	0.4062	1.5649	1.1588	0.5889	1.0589	0.4700	0.3916	0.8861	0.4945
28	15/1	0.5019	1.1142	0.6123	0.5691	1.0689	0.4998	0.3860	1.0627	0.6768
29	15/4	0.5019	1.1665	0.6645	0.5691	0.8125	0.2435	0.3860	0.8999	0.5140
30	16/18	0.8497	1.3972	0.5476	0.7690	1.2453	0.4763	0.6924	0.9831	0.2908
31	16/26	0.8497	1.0558	0.2061	0.7690	1.0392	0.2702	0.6924	1.0041	0.3117
32	17/15	0.7617	1.2445	0.4828	0.7895	1.4993	0.7097	0.7333	1.1457	0.4124
33	17/26	0.7617	1.1715	0.4098	0.7895	1.1400	0.3505	0.7333	1.1345	0.4012
34	18/19	0.5153	0.7250	0.2097	0.4685	0.9189	0.4504	0.3548	0.8297	0.4749
35	18/22	0.5153	0.7222	0.2068	0.4685	0.7987	0.3303	0.3548	0.8137	0.4589
36	18/30	0.5153	0.7201	0.2048	0.4685	0.9072	0.4388	0.3548	0.7690	0.4141
37	19/3	0.4845	0.9552	0.4708	0.6449	0.9438	0.2989	0.5873	0.8489	0.2616
38	19/7	0.4845	0.9611	0.4766	0.6449	0.9035	0.2586	0.5873	0.8987	0.3114
39	19/12	0.4845	0.8479	0.3634	0.6449	0.9154	0.2705	0.5873	0.8276	0.2403
40	20/17	0.4394	0.7739	0.3346	0.3802	0.7974	0.4172	0.4709	0.7457	0.2748
41	20/22	0.4394	0.6395	0.2	0.3802	0.7305	0.3503	0.4709	0.7419	0.2711
42	20/30	0.4394	0.6443	0.2049	0.3802	0.8271	0.4469	0.4709	0.7019	0.2310
43	21/17	0.5186	0.8968	0.3781	0.6113	0.8713	0.2600	0.4974	0.8706	0.3732
44	21/19	0.5186	0.7236	0.2050	0.6113	0.9173	0.3060	0.4974	0.8283	0.3309
45	21/33	0.5186	0.7189	0.2003	0.6113	0.9060	0.2947	0.4974	0.7679	0.2705
46	22/23	0.6223	2.1725	1.5502	0.7157	1.7221	1.0064	0.7265	1.1746	0.4481
47	22/34	0.6223	1.6425	1.0202	0.7157	1.0922	0.3764	0.7265	0.9933	0.2668
48	23/11	0.6631	0.8675	0.2044	0.7619	1.0426	0.2806	0.5196	1.0367	0.5172
49	23/13	0.6631	1.0787	0.4156	0.7619	1.0723	0.3104	0.5196	0.8966	0.3770
50	24/21	1.2617	1.7479	0.4862	0.8035	1.6088	0.8052	0.6674	1.3393	0.6718
51	24/34	1.2617	1.4622	0.2006	0.8035	1.0261	0.2226	0.6674	0.9320	0.2646
52	25/15	0.7649	0.9650	0.2001	0.8834	1.1359	0.2525	0.6013	0.8271	0.2258
53	25/18	0.7649	1.2317	0.4668	0.8834	1.1018	0.2184	0.6013	0.8631	0.2618
54	26/28	0.6922	0.8922	0.2	0.7068	1.0879	0.3811	0.6232	0.9171	0.2939
55	26/36	0.6922	1.1699	0.4777	0.7068	1.1839	0.4771	0.6232	0.8351	0.2119
56	27/25	0.7730	1.0415	0.2684	0.7513	1.1373	0.3861	0.5552	0.8355	0.2803
57	27/36	0.7730	1.0747	0.3017	0.7513	1.1180	0.3667	0.5552	0.7876	0.2324
58	28/29	0.6407	1.0107	0.3700	0.6982	1.0418	0.3436	0.6421	0.8758	0.2337
59	28/32	0.6407	1.2344	0.5936	0.6982	1.0358	0.3376	0.6421	1.0207	0.3785
60	29/17	0.4327	0.7702	0.3375	0.5109	0.7950	0.2841	0.4240	0.7419	0.3179
61	29/19	0.4327	0.6333	0.2006	0.5109	0.8176	0.3068	0.4240	0.7406	0.3166
62	29/22	0.4327	0.6369	0.2042	0.5109	0.7283	0.2174	0.4240	0.7396	0.3157
63	30/27	0.6532	1.2775	0.6243	0.8366	1.0994	0.2628	0.7099	1.0756	0.3657
64	30/32	0.6532	1.6800	1.0267	0.8366	1.2936	0.4570	0.7099	1.2639	0.5540
65	32/27	0.9550	1.1584	0.2033	0.8073	1.0246	0.2173	0.7196	0.9372	0.2176
66	31/29	0.9550	1.3655	0.4105	0.8073	1.3058	0.4985	0.7196	1.1050	0.3854
67	32/33	0.9764	1.7972	0.8208	0.8643	1.4378	0.5735	0.8565	1.2067	0.3501
68	32/42	0.9764	1.5160	0.5395	0.8643	1.3310	0.4668	0.8565	1.2093	0.3528
69	33/21	1.0322	1.2324	0.2002	0.9533	1.2491	0.2958	0.6543	1.0313	0.3769
70	33/23	1.0322	1.3133	0.2811	0.9533	1.2642	0.3109	0.6543	0.8621	0.2078
71	34/31	0.9301	1.4912	0.5611	0.7803	1.2875	0.5072	0.7053	1.0342	0.3289
72	34/42	0.9301	1.2242	0.2941	0.7803	1.0772	0.2969	0.7053	0.9166	0.2113
73	35/25	0.6387	1.1081	0.4694	0.8158	1.1945	0.3786	0.6656	0.8934	0.2277
74	35/28	0.6387	0.8904	0.2517	0.8158	1.0847	0.2688	0.6656	0.9150	0.2494
75	36/38	0.6371	1.1541	0.5169	0.7608	1.0792	0.3184	0.5323	0.9353	0.4029
76	37/35	0.5775	0.7776	0.2001	0.6144	0.9168	0.3024	0.5166	0.7484	0.2318
77	38/40	1.0442	1.2689	0.2248	1.0054	1.3304	0.3251	0.8711	1.1468	0.2757
78	39/37	0.7545	1.0167	0.2622	0.8100	1.2044	0.3944	0.5826	0.8183	0.2357
79	40/41	0.6165	1.7335	1.1170	0.8570	1.0630	0.2060	0.7265	0.9405	0.2140
80	41/31	1.5237	1.7237	0.2	0.9630	1.5022	0.5392	0.8555	1.1556	0.3001
81	41/33	1.5237	1.7267	0.2030	0.9630	1.3986	0.4357	0.8555	1.1531	0.29756
82	42/39	0.7104	0.9140	0.2036	0.6275	0.9765	0.3490	0.4800	0.7453	0.26530

5. CONCLUSION

This paper proposes three different optimization methods, PSO, GA and DE dealing with the problem of coordination of directional overcurrent relays. These techniques are applied on two distribution networks with 9 and 15 buses integrating distributed generators in order to determine the most efficient method to solve this problem with the integration of DGs, the objective function and the time of convergence obtained by each method are compared between them. The comparative analysis shows that the differential evolution gives optimal values of the objective function and a shorter convergence time compared to the other methods for both distribution networks. Even more, the CTI values obtained by DE are found to be the most optimal, which explains the choice of DE as the method that offers the most satisfactory results among the methods investigated in this work. Therefore, DE can be regarded as the most efficient method to reach the best solution respecting the constraint of coordination between relays in the presence of DGs.

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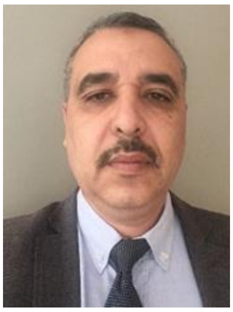

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