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OPTIMAL COORDINATION OF DOCRS USING GA WITH INTEGRATION OF DGS IN DISTRIBUTION NETWORKS

Z. El Idrissi [1] **T. Haidi** [1,2] **F. Elmariami** [1] **A. Belfqih** [1]

1. Laboratory of Electric Systems and Energy, ENSEM, University of Hassan II, Casablanca, Morocco
zineb.elidrissy@gmail.com, f_elmariami@yahoo.fr, a-belfqih@hotmail.com
2. Department of Electrical Engineering, Laboratory of Systems Engineering, EHTP, Casablanca, Morocco
touriahaidi60@gmail.com

Abstract- Nowadays, the connection of distributed generators DGs to distribution grids is important to reduce power losses and guarantee electricity production. With the integration of these generators, the distribution system is experiencing an increase in short circuit values and, as a result, current overcurrent relay settings are resulting in poor relay coordination. Recently, the problem of relay coordination has been solved by various optimization techniques based on artificial intelligence. In this paper, the optimal coordination of overcurrent relays was performed using the genetic algorithm. The objective of this technique is the minimization of the sum of the operating times of the directional overcurrent relay DOCR by determining the optimal *TDS* and *PS* parameters of all relays taking into account the particular constraints. In addition, appropriate combinations of primary and backup relays are selected to address the coordination problem due to DG power and network topology changes. The simulation is performed using MATLAB R2021a software on a 9-bus interconnected distribution system equipped with DOCRs.

Keywords: Distributed Generator, Distribution Networks, Genetic Algorithm, Directional Overcurrent, Optimal Coordination.

1. INTRODUCTION

Electricity has an important role in the development of countries. It is one of the determining elements of national economic development and the improvement of living conditions of the population. The strategic objective is to reduce dependence on energy imports. In the long term, Morocco has the ambition to become an energy exporter to European and African markets, as it is aware of the potential it has in terms of renewable energy (wind and solar potential) [1]. The wind profiles in the north and south of Morocco are particularly favorable for the development of wind energy.

In addition, Morocco enjoys excellent sunshine. These advantages have allowed the government to stimulate the development of solar and wind energy, which explains why Morocco has a real card to play in the field of renewable energy [2]. Following a sharp increase in annual energy demand, the connection of DGs to the distribution networks is considered as a potential solution [3], [4].

The integration of DGs has negative effects on the performance of the distribution network in terms of fault current, this increase depends on the location of DGs relative to the fault and their size [5]. This change to the network can lead to protection coordination problems. In order to avoid accidental destruction of expensive equipment and to ensure continuity of service, protection of the power system is a necessity [6]. The primary relay must operate in case of a fault in its operating area. If it cannot clear the fault, the backup relay must take over this function. Primary and backup relays may malfunction if they are not properly coordinated. Therefore, coordination of protective relays is a critical concern for the protection of the electrical system [7].

This property of the protection system is also referred to as selectivity, which makes it possible to obtain maximum continuity of service with minimum disconnections from the grid. The protection system must be as fast and economical as possible. To achieve these objectives, the existing relays in the electrical system must be coordinated [8], [9]. Digital DOCRs are a technical and economical choice, as they have much higher capacities than conventional electromechanical relays, which is why they are the most widely used in distribution networks [10].

The coordination of DOCR is considered as an optimization problem, it was performed using optimization methods. These methods aim to determine the optimal parameters of the setting which are the time dial setting *TDS* or the time multiplier setting *TMS* and the pickup current I_P [11]. The genetic algorithm is an adaptive method applied to solve the optimal coordination problem. It is a powerful and efficient heuristic optimization technique [12]. It has been applied in [13] as a multi-objective optimization algorithm whose objectives are the minimization of the size of the FCL and the optimal settings of the protection devices, in [14] this method is applied to maximize the penetration of

DGs in distribution networks by seeking the optimal size and location of these generators taking into account the coordination of protection relays. The GA has been implemented in this work because of their effectiveness in existing studies in the literature and its reduced computational time.

The sections of this work are organized as follows: the problem statement is detailed in the second section, section 3 presents the genetic algorithm used to have an optimal coordination of the protection relays, section 4 contains the simulation results of 9-bus interconnected distribution network in the presence of DGs. And finally, the conclusion is provided in the last section.

2. PROBLEM STATEMENT

2.1. Objective Function

The DOCR coordination problem is solved by different optimization methods taking into account the coordination, reliability, sensitivity and relay characteristics constraints. The objective function of this problem is the minimization of the sum of the operating times of all existing relays in the network as shown in the following Equation (1) [15].

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

where, $t_{ij}{}^{p}$ and $t_{ij}{}^{b}$ represents the operating times of the primary relay and the backup relay, respectively. The N and M are the number of fault locations studied and the number of relays, respectively [16].

2.2. Coordination Constraints

Coordination Time Interval CTI is the difference between the backup relay operating time t_b and the primary relay operating time t_p for all pairs of primary and backup R_P/R_B relays, the value of CTI is between 0.2 and 0.5 s, usually taken as 0.3 s [11]. It depends on some factors such as circuit breaker operating time (5 cycles), relay overtravel, tolerance and relay setting errors as shown in Table 1 [17]. To maintain coordination, CTI must be imposed between a pair of R_P/R_B relays. The coordination constraints of the protection are expressed in the Equation (2) [18], [19].

$$t_b - t_p \geq CTI \tag{2}$$

Table 1. CTI with field calibration [19]

	Static	Electromechanical	Induction disk
Circuit breaker opening time	0.08	0.08	0.08
Relay overtravel	0.00	0.10	0.10
Tolerance and relay setting errors	0.12	0.12	0.22
Total CTI	0.2	0.3	0.4

2.3 Characteristics of Overcurrent Relays

2.3.1. Operating Time

Based on IEC60255, the operating time of DOCR is expressed in Equation (3) as follows [20]:

$$t = TDS \frac{A}{\left(\frac{I_F}{I_P} \right)^B - 1} \tag{3}$$

where, I_F represent the fault current, A and B are the constants which are defined as mentioned in Table 2 [21]. The current I_P is product of plug setting PS and current transformer ratio CTR as expressed in Equation (4).

$$PS = \frac{I_P}{CTR} \tag{4}$$

Table 2. Different types of overcurrent relay characteristics according to IEC60255 standard [21]

Characteristics of the relays	A	B
Normal inverse	0.14	0.02
Very inverse	13.5	1
Extremely inverse	80	2
Long-time inverse	120	1

The constraints of selectivity, reliability and sensitivity must be taken into account, in order to maintain coordination between the primary and backup relays, to ensure that the relay operates within the operating time limits when a fault occurs its protection zone and to ensure that the fault is within the protection zone by adjusting the relay parameters [22].

2.3.2. Reliability Constraint

The relay needs a minimum time to trip and it should not take long to do so. Equation (5) presents the operating time limits in which the relay must operate, $t_{\min}$ is the minimum operating time and $t_{\max}$ is the maximum operating time [23]. In this work, $t_{\min}$ is 0.1 s and $t_{\max}$ is 4 s of all relays.

$$t_{\min} \leq t \leq t_{\max} \tag{5}$$

2.3.3. Sensitivity Constraint

The limits of TDS and PS are expressed in formulas (6) and (7), the minimum and maximum values of TDS are $TDS_{\min}$ and $TDS_{\max}$, generally varied between 0.1 and 1.1 s [24].

$$TDS_{\min} \leq TDS \leq TDS_{\max} \tag{6}$$

$$PS_{\min} \leq PS \leq PS_{\max} \tag{7}$$

The user can take the plug current PS in a range where the minimum value $PS_{\min}$ is the greater of the minimum available tap and the product of a safety factor by the maximum load current $I_{L\max}$ divided by the CTR, and the maximum value $PS_{\max}$ is the smaller value between the maximum available tap and two-thirds of the minimum fault current $I_{F\min}$ divided by the CTR, as shown in the following Equations [25].

$$PS_{\min} = \max \left\{ 0.5 \times \frac{(1.25 \times I_{L\max})}{CTR} \right\} \tag{8}$$

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

3. GENETIC ALGORITHM GA

Genetic algorithms are a type of iterative stochastic algorithms, which can find the optimal solution of any optimization problem, regardless of the type of objective function. GA starts from a randomly generated initial population, called chromosomes, to reach the optimal point in the search space through production, crossover, mutation and selection operations. The population size is taken as N and D is the number of variables that represent the dimensions of each element of the population. The Crossover Rate CR, Mutation Rate MR, iterations as well as the population size are shown in Table 3.

Table 3. Values of the parameters of the GA for the studied system

Number of population (N)	Number of iterations ($iter$)	Crossover rate (CR)	Mutation rate (MR)
250	970	0.9	0.1

A protection scheme with n directional overcurrent relays will have ($2\times n$), variables. The first n variables are the TDS values and the second n variables are the PS values of the relays [11]. For the case of a 9-bus interconnected distribution system, its protection scheme contains 24 relays so it will have 48 variables where the first 24 variables are the TDS values and the second 24 variables are the PS values. The operating time of relay i using the genetic algorithm and the vector of variables are expressed, respectively, in Equations (10) and (11).

$$t_i = X_i \frac{0.14}{\left(\dfrac{I_F}{CTR\times X_{i+24}}\right)^{0.02} - 1} \tag{10}$$

$$X = \{X_1; X_2; ...; X_{48}\} \tag{11}$$

The different steps of the genetic algorithm are summarized in the flowchart shown in Figure 1.

4. RESULTS AND DISCUSSION

In this study, two scenarios are proposed to evaluate the behavior of the coordination of the protection relays in the studied system with the integration of distributed generators DGs. The first scenario is to determine the optimal values of the parameters of 24 relays existing in a 9-bus interconnected distribution network using the genetic algorithm. This algorithm was used to ensure coordination between relays taking into account the sensitivity and reliability constraints and especially the coordination constraint. After connecting four distributed generators to the grid, the short circuit current values have been increased, which will influence the coordination of the relays with the same optimal parameters of this scenario. The second scenario is the use of the genetic algorithm on the network containing the four generators to find new parameters and solve the coordination problem.

4.1. Scenario 1

The genetic algorithm is applied to a 33 kV, 9-bus interconnected distribution system, supplied by a single 100 MVA power source. The primary and backup relay R_P/R_B pairs, the maximum load current $I_{L\max}$ and maximum and minimum short circuit current values in all fault locations are presented in Table 4.

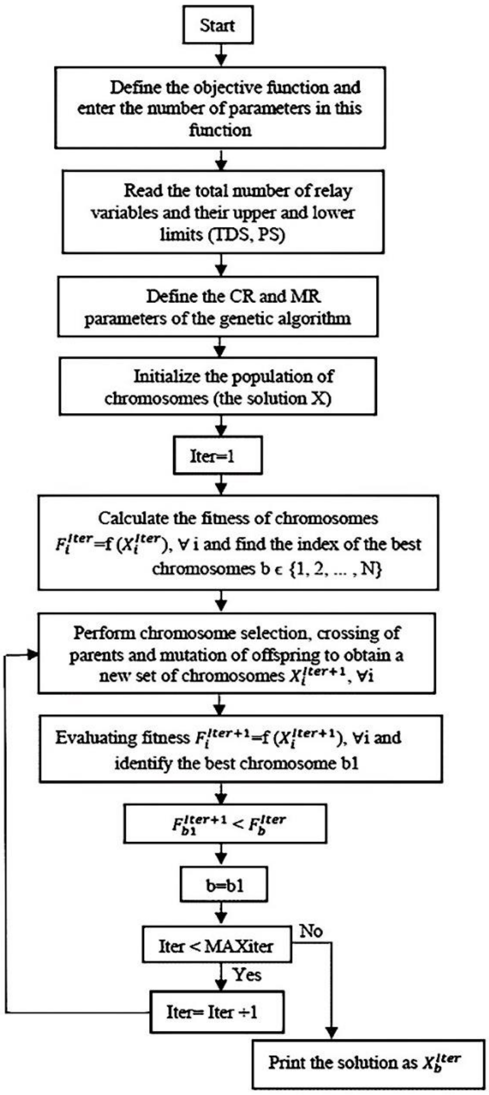

Figure 1. Flowchart of different stages of GA

Table 4. Primary and backup relay pairs, maximum load current and short circuit current values (without DGs) [26]

Fault location	R_P	R_B	$I_{L\max}$ (A)	$I_{F\max}$ (A)	$I_{F\min}$ (A)
A	R_1	R_{15}, R_{17}	121.74	4863.6	1361.6
	R_2	R_4	212.74	1634.4	653.6
B	R_3	R_1	21.74	2811.4	1124.4
	R_4	R_6	21.74	2610.5	1044.2
C	R_5	R_3	78.26	1778	711.2
	R_6	R_8, R_{23}	78.26	4378.5	1226
D	R_7	R_5, R_{23}	78.26	4378.5	1226
	R_8	R_{10}	78.26	1778	711.2
E	R_9	R_7	21.74	2610.5	1044.2
	R_{10}	R_{12}	21.74	2811.4	1124.4
F	R_{11}	R_9	121.74	1634.4	653.6
	R_{12}	R_{14}, R_{21}	121.74	2811.4	787.2
G	R_{13}	R_{11}, R_{21}	30.44	3684.5	1031.7
	R_{14}	R_{16}, R_{19}	30.44	4172.5	1168.3
H	R_{15}	R_{13}, R_{19}	30.44	4172.5	1168.3
	R_{16}	R_2, R_{17}	30.44	3684.5	1031.7
I	R_{17}	--	441.3	7611.2	1293.9
	R_{18}	R_2, R_{15}	441.3	2271.7	1953.7
J	R_{19}	--	410.87	7435.8	1264.1
	R_{20}	R_{13}, R_{16}	410.87	2624.2	2256.8
K	R_{21}	--	441.3	7611.2	1293.9
	R_{22}	R_{11}, R_{14}	441.3	2271.2	1953.7
L	R_{23}	--	506.52	7914.7	1345.5
	R_{24}	R_5, R_8	506.52	1665.5	1432.3

The 24 directional overcurrent relays are digital, in which *PS* and *TDS* are continuous. They have the same current transformer ratio *CTR* of 500/1. The relays $\{R_{17}, R_{19}, R_{21}, R_{23}\}$ are assumed without backup. The maximum and minimum PS values for all DOCRs are calculated based on the Equations (8) and (9). The characteristic constants of relays A and B are 0.14 and 0.02 respectively according to IEC60255 standards. The *CTI* is considered to be 0.3 s.

The simulation results are obtained using MATLAB R2021a. The optimal *PS* and *TDS* parameters for the 24 DOCRs are given in Table 5. The convergence curve of the objective function using the genetic algorithm is shown in Figure 2. The sum of operating times of relays in this network, which corresponds to the objective function, is equal to 51.722 s and the computation time of the genetic algorithm is 47.548 s.

Table 5. Optimal relay settings without DGs using GA

Number of relays	*TDS*	*PS*
R_1	0.1528	0.8464
R_2	0.2314	0.5319
R_3	0.1928	0.5
R_4	0.1620	0.5756
R_5	0.2604	0.5
R_6	0.2220	0.5
R_7	0.1	1.1234
R_8	0.3867	0.5
R_9	0.1003	0.8326
R_{10}	0.2562	0.5
R_{11}	0.2597	0.5001
R_{12}	0.1246	1.0496
R_{13}	0.2836	0.5
R_{14}	0.2360	0.5061
R_{15}	0.2411	0.5
R_{16}	0.3230	0.5
R_{17}	0.1042	1.1033
R_{18}	0.1	1.1033
R_{19}	0.1	1.1049
R_{20}	0.1	1.5819
R_{21}	0.1	1.1158
R_{22}	0.1	1.1033
R_{23}	0.1087	1.2663
R_{24}	0.1	1.2663
Objective function	51.7220 s	
Convergence time	47.547697 s	

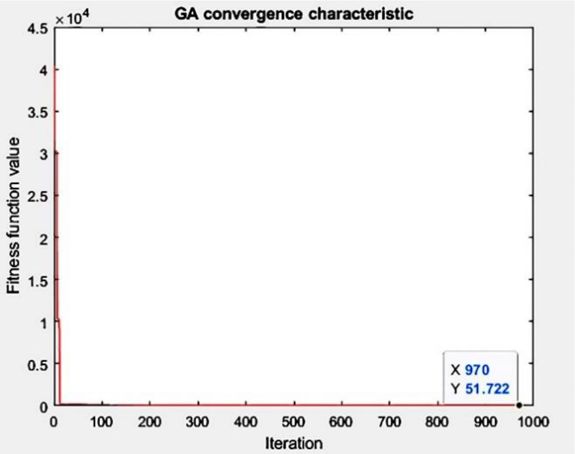

Figure 2. Evolution of the objective function using the GA algorithm without DG

Table 6 shows the primary relay operating time t_p and the backup relay operating time t_b, as well as the *CTI* between 32 primary and backup relays R_P/R_B pairs.

Table 6. Operating times of primary and backup relays and *CTI* values without DGs

Relays R_P/R_B Pairs	t_p	t_b	*CTI*
R_1/R_{15}	0.4274	0.9789	0.5515
R_1/R_{17}	0.4274	0.7998	0.3724
R_2/R_4	0.8759	1.3714	0.4955
R_3/R_1	0.5442	1.0838	0.5396
R_4/R_6	0.5031	1.0715	0.5684
R_5/R_3	0.9111	1.2771	0.3661
R_6/R_8	0.5274	1.6753	1.1480
R_6/R_{23}	0.5274	1.1438	0.6164
R_7/R_5	0.3339	1.1283	0.7944
R_7/R_{23}	0.3339	1.1438	0.8099
R_8/R_{10}	1.3528	1.6973	0.3444
R_9/R_7	0.3755	1.1220	0.7465
R_{10}/R_{12}	0.7232	1.1359	0.4127
R_{11}/R_9	0.9501	1.5495	0.5994
R_{12}/R_{14}	0.5110	1.4391	0.9281
R_{12}/R_{21}	0.5110	2.0261	1.5152
R_{13}/R_{11}	0.7181	1.2644	0.5463
R_{13}/R_{21}	0.7181	1.1316	0.4135
R_{14}/R_{16}	0.5730	1.4440	0.8710
R_{14}/R_{19}	0.5730	0.9277	0.3546
R_{15}/R_{13}	0.5828	1.2676	0.6848
R_{15}/R_{19}	0.5828	0.9277	0.3448
R_{16}/R_2	0.8180	1.1786	0.3606
R_{16}/R_{17}	0.8180	1.1575	0.3394
R_{18}/R_2	0.4876	0.7961	0.3085
R_{18}/R_{15}	0.4876	0.8041	0.3165
R_{20}/R_{13}	0.5767	0.8824	0.3057
R_{20}/R_{16}	0.5767	1.0052	0.4285
R_{22}/R_{11}	0.4876	0.8661	0.3785
R_{22}/R_{14}	0.4876	0.7918	0.3042
R_{24}/R_5	0.7168	1.0262	0.3094
R_{24}/R_8	0.7168	1.5237	0.8069

As it is shown in the results, the genetic algorithm has given optimal parameters to ensure the coordination between the 32 pairs of relays in the distribution network by respecting coordination constraints, *CTI* is greater than 0.3 s for each primary/backup pair as well as sensitivity and reliability constraints are also well respected.

Due to the increasing inclusion of DGs in the grid, the protection systems have changed gradually. To test the influence of these generators on relay coordination, four distributed generators connected to the 9-bus interconnected network are considered. Therefore, each DG is designed with ratings of 8 *MW* and 33 *kV*. They are connected as DG1 to Bus7, DG2 to Bus5, DG3 to Bus9, and DG4 to Bus3. Figure 3 shows the diagram of 4 generators connected to the studied network [27].

The short-circuit current values have increased with the integration of DGs into the distribution system. In addition, other primary and backup relay pairs are selected, so there will be 44 pairs of R_P/R_B relays as shown in Table 7.

Table 8 gives the primary relay operating time t_p and the backup relay operating time t_b, calculated with the same *TDS* and *PS* found in this scenario, as well as the *CTI* between 32 pairs of primary and backup R_P/R_B relays.

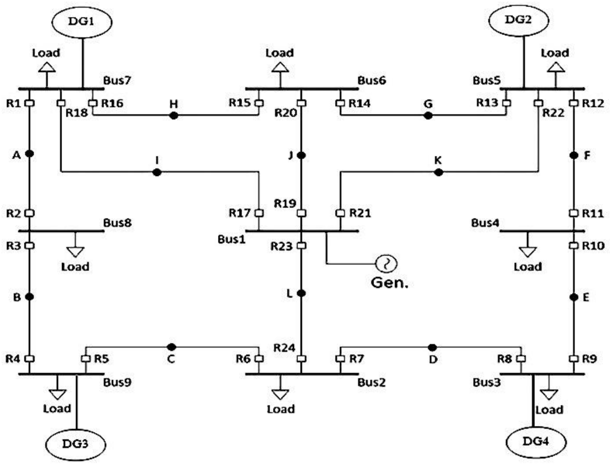

Figure 3. Diagram of a 9-bus interconnected distribution system with four distributed generators [27]

Table 7. Primary and backup relay pairs and short circuit current values (with DGs)

Fault location	R_P	R_B	$I_{F\max}$ (A)	$I_{F\min}$ (A)
A	R_1	R_{15}	5591,6	2099,6
	R_1	R_{17}	5591,6	1835,7
	R_2	R_4	2254,4	1309,6
B	R_3	R_1	3431,4	1852,4
	R_4	R_6	3284,5	1776,2
C	R_5	R_3	2452	1331,2
	R_6	R_8	5110.5	1901
	R_6	R_{23}	5110.5	2030
D	R_7	R_5	5110.5	1900
	R_7	R_{23}	5110.5	2030
	R_8	R_{10}	2453	1331,2
E	R_9	R_7	3285.5	1776.2
	R_{10}	R_{12}	3431.4	1852.4
F	R_{11}	R_9	2254.4	1328.6
	R_{12}	R_{14}	3539.4	1525.2
	R_{12}	R_{21}	3539.4	1835.7
G	R_{13}	R_{11}	4412.5	1651.7
	R_{13}	R_{21}	4412.5	1835.7
	R_{14}	R_{16}	4910.5	1896.3
	R_{14}	R_{19}	4910.5	1972.3
H	R_{15}	R_{13}	4910.5	1996.3
	R_{15}	R_{19}	4910.5	1972.3
	R_{16}	R_2	4412.5	1651.7
	R_{16}	R_{17}	4412.5	1835.7
I	R_{17}	R_{20}	8415.2	738
	R_{17}	R_{22}	8415.2	728
	R_{17}	R_{24}	8415.2	732
	R_{18}	R_2	2999.7	1651.7
	R_{18}	R_{15}	2999.7	2099.6
J	R_{19}	R_{18}	8239.8	728
	R_{19}	R_{22}	8239.8	728
	R_{19}	R_{24}	8239.8	732
	R_{20}	R_{13}	3362.2	1996.3
	R_{20}	R_{16}	3362.2	1896.3
K	R_{21}	R_{18}	8415.2	728
	R_{21}	R_{20}	8415.2	738
	R_{21}	R_{24}	8415.2	732
	R_{22}	R_{11}	2999.2	1651.7
	R_{22}	R_{14}	2999.2	1525.2
L	R_{23}	R_{18}	8718.7	728
	R_{23}	R_{20}	8718.7	738
	R_{23}	R_{22}	8718.7	728
	R_{24}	R_5	2397.5	1900
	R_{24}	R_8	2397.5	1901

Table 8. Operating times of primary and backup relays and *CTI* values with DGs

Relay R_P/R_B Pairs	t_P	t_b	CTI
R_1/R_{15}	0.4037	0.8259	0.4222
R_1/R_{17}	0.4037	0.5947	0.1910
R_2/R_4	0.7417	0.6378	-0.1039
R_3/R_1	0.5018	0.9225	0.4207
R_4/R_6	0.4546	0.9228	0.4682
R_5/R_3	0.7803	0.6519	-0.1284
R_6/R_8	0.4996	1.3535	0.8539
R_6/R_{23}	0.4996	0.73	0.2304
R_7/R_5	0.3101	0.9116	0.6015
R_7/R_{23}	0.3101	0.73	0.4199
R_8/R_{10}	1.1584	0.8661	-0.2923
R_9/R_7	0.3329	0.8061	0.4732
R_{10}/R_{12}	0.6668	0.9283	0.2615
R_{11}/R_9	0.8085	0.5025	-0.306
R_{12}/R_{14}	0.4483	0.8134	0.3651
R_{12}/R_{21}	0.4483	0.5763	0.128
R_{13}/R_{11}	0.6718	0.8569	0.1851
R_{13}/R_{21}	0.6718	0.5421	-0.1297
R_{14}/R_{16}	0.5407	1.2279	0.6872
R_{14}/R_{19}	0.5407	0.6823	0.1416
R_{15}/R_{13}	0.55	0.9130	0.363
R_{15}/R_{19}	0.55	0.5173	-0.0327
R_{16}/R_2	0.7653	0.8084	0.0431
R_{16}/R_{17}	0.7653	0.5833	-0.182
R_{17}/R_{20}	0.2604	0.8244	0.564
R_{17}/R_{22}	0.2604	0.5752	0.3148
R_{17}/R_{24}	0.2604	0.6506	0.3902
R_{18}/R_2	0.4064	1.5922	1.1858
R_{18}/R_{15}	0.4064	1.5621	1.1557
R_{19}/R_{18}	0.2521	0.5424	0.2903
R_{19}/R_{22}	0.2521	0.5424	0.2903
R_{19}/R_{24}	0.2521	0.6090	0.3569
R_{20}/R_{13}	0.4767	1.8139	1.3372
R_{20}/R_{16}	0.4767	2.0663	1.5896
R_{21}/R_{18}	0.2510	0.5752	0.3242
R_{21}/R_{20}	0.2510	0.8244	0.5734
R_{21}/R_{24}	0.2510	0.6506	0.3996
R_{22}/R_{11}	0.4064	1.6827	1.2763
R_{22}/R_{14}	0.4064	1.5467	1.1403
R_{23}/R_{18}	0.2826	0.5303	0.2477
R_{23}/R_{20}	0.2826	0.7357	0.4531
R_{23}/R_{22}	0.2826	0.5303	0.2477
R_{24}/R_5	0.5188	1.6786	1.1598
R_{24}/R_8	0.5188	2.4925	1.9737

It can be seen that 18 coordination violations appear in Table 8, which are shown in bold. The time intervals of some R_P/R_B relays are less than 0.3 s and present serious conditions to the system operation. Relay pairs that have poor coordination are $\{R_1/R_{17}$, R_2/R_4, R_5/R_3, R_6/R_{23}, R_8/R_{10}, R_{10}/R_{12}, R_{11}/R_9, R_{12}/R_{21}, R_{13}/R_{11}, R_{13}/R_{21}, R_{14}/R_{19}, R_{15}/R_{19}, R_{16}/R_2, R_{16}/R_{17}, R_{19}/R_{18}, R_{19}/R_{22}, R_{23}/R_{18}, $R_{23}/R_{22}\}$.

It can be concluded that the coordination of the relays can be re-established when the setting of these relays is readjusted with a new setting different from the original one before the connection of the DGs to the distribution network. It is in this context that a second scenario must be implemented.

4.2. Scenario 2

The second scenario consists of applying the genetic algorithm to find a new setting for 24 relays in the network taking into account the presence of DGs. The steps of the genetic algorithm are the same presented in the flowchart except the first step which is the change of the parameters of this function namely the short circuit current and the pairs of R_P/R_B relays.

Table 9 presents the new optimal parameters *TDS* and *PS* by applying genetic algorithm on distribution network with connection of DGs. The evolution of the objective function is presented in Figure 4, its value is 84.7535 s and calculation time of this algorithm is 77.420 s.

Table 9. Optimal relay settings with DGs using GA

Number of relays	*TDS*	*PS*
R_1	0.1925	1.0591
R_2	0.3736	0.5354
R_3	0.2975	0.6316
R_4	0.2297	1.2630
R_5	0.2415	0.5575
R_6	0.2792	0.6166
R_7	0.1	1.6347
R_8	0.3237	0.5
R_9	0.3088	0.9764
R_{10}	0.3718	0.7567
R_{11}	0.4662	0.5
R_{12}	0.4033	0.5209
R_{13}	0.2619	0.5917
R_{14}	0.4765	0.5
R_{15}	0.2633	0.5
R_{16}	0.4198	0.5
R_{17}	0.2568	1.1247
R_{18}	0.2481	1.1330
R_{19}	0.1653	1.3523
R_{20}	0.1537	1.2475
R_{21}	0.2149	1.2545
R_{22}	0.1583	1.1600
R_{23}	0.1240	1.5960
R_{24}	0.1663	1.6060
Objective function	84.7535 s	
Convergence time	77.420441 s	

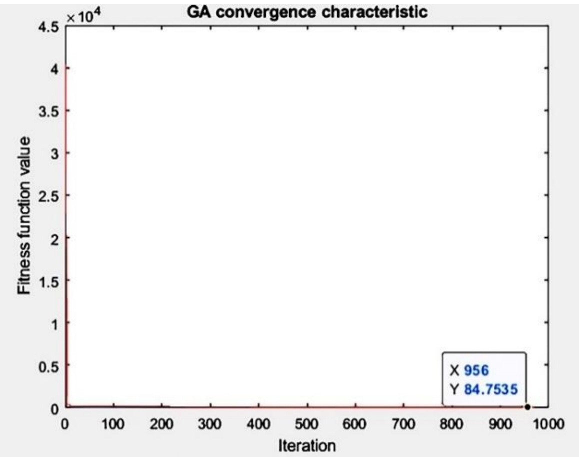

Figure 4. Evolution of the objective function using the GA algorithm in the presence of DGs

The primary and backup relay operating times t_p and t_b calculated with the new *TDS* and *PS* parameters, as well as the *CTI* between 44 primary and backup R_P/R_B relay pairs are given in Table 10.

It is clear that the *CTI* is greater than 0.3 s for the 44 pairs of R_P/R_B relays. We can deduce that the application of the genetic algorithm to the 9-bus interconnected distribution network can solve the coordination problem in the presence of DGs while respecting all constraints.

Table 10. Operating times of primary and backup relays and *CTI* values with DGs (with new parameters)

Relay R_P/R_B Pairs	t_p	t_b	*CTI*
R_1/R_{15}	0.5582	0.9019	0.3437
R_1/R_{17}	0.5582	1.4902	0.9320
R_2/R_4	1.2013	1.6565	0.4552
R_3/R_1	0.8524	1.4481	0.5957
R_4/R_6	0.9592	1.3317	0.3725
R_5/R_3	0.7607	1.1399	0.3792
R_6/R_8	0.6766	1.1331	0.4565
R_6/R_{23}	0.6766	1.0763	0.3996
R_7/R_5	0.3749	0.8960	0.5210
R_7/R_{23}	0.3749	1.0763	0.7013
R_8/R_{10}	0.9698	1.5862	0.6164
R_9/R_7	1.1121	1.4338	0.3217
R_{10}/R_{12}	1.1544	1.7022	0.5477
R_{11}/R_9	1.4516	1.7517	0.3001
R_{12}/R_{14}	1.0538	1.6323	0.5785
R_{12}/R_{21}	1.0538	1.3744	0.3206
R_{13}/R_{11}	0.6618	1.5384	0.8782
R_{13}/R_{21}	0.6618	1.2846	0.6244
R_{14}/R_{16}	1.0872	1.5956	0.5085
R_{14}/R_{19}	1.0872	1.4111	0.3240
R_{15}/R_{13}	0.6007	0.9172	0.3165
R_{15}/R_{19}	0.6607	1.0098	0.4091
R_{16}/R_2	0.9945	1.3097	0.3153
R_{16}/R_{17}	0.9945	1.4611	0.4667
R_{17}/R_{20}	0.6467	0.9860	0.3393
R_{17}/R_{22}	0.6467	0.9507	0.3040
R_{17}/R_{24}	0.6467	1.3964	0.7497
R_{18}/R_2	1.0248	2.5878	1.5630
R_{18}/R_{15}	1.0248	1.7059	0.6811
R_{19}/R_{18}	0.4514	1.3751	0.9237
R_{19}/R_{22}	0.4214	0.8943	0.4429
R_{19}/R_{24}	0.4514	1.2839	0.8326
R_{20}/R_{13}	0.6280	1.9872	1.3592
R_{20}/R_{16}	0.6280	2.6852	2.0572
R_{21}/R_{18}	0.5645	1.4601	0.8955
R_{21}/R_{20}	0.5645	0.9860	0.4214
R_{21}/R_{24}	0.5645	1.3964	0.8318
R_{22}/R_{11}	0.6634	3.0208	2.3574
R_{22}/R_{14}	0.6634	3.0875	2.4241
R_{23}/R_{18}	0.3544	1.3436	0.9892
R_{23}/R_{20}	0.3544	0.9010	0.5466
R_{23}/R_{22}	0.3544	0.8735	0.5190
R_{24}/R_5	1.0527	1.7340	0.6813
R_{24}/R_8	1.0527	2.0866	1.0339

5. CONCLUSION

The increase in the annual demand for electrical energy is driving the power sector to integrate distributed generators, but this integration has a negative effect on the protection of the grid. In order to test the behavior of DGs on the coordination of protective relays, two scenarios are proposed in this paper. The first scenario is the application of the GA genetic algorithm on a 9-bus interconnected distribution network in order to obtain an optimal coordination of the DOCRs. With the installation of distributed generators in this network, the short-circuit current values are changed. Due to this change, relay coordination was lost between 18 primary/backup relay pairs. In the second scenario, the genetic algorithm was implemented on the distribution network in the presence of DGs to restore relay coordination. The simulation results show that this algorithm provides an efficient and robust high-quality solution.

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BIOGRAPHIES

Zineb El Idrissi was born in Fes, Morocco, 1993. She received a state engineering degree in electrical engineering in 2016 from National School of Electricity and Mechanics (ENSEM), Hassan II University, Casablanca, Morocco. She is currently a Ph.D. student in the research team "Electrical Networks and Static Converters" in the same university. Her research interests include distributed generation in distribution networks, renewable energies, and their impact on protection coordination.

Touria Haidi received a diploma in electrical engineering from Hassania School of Public Works (EHTP), Casablanca, Morocco, a post-graduate certificate in information processing from Ben M'sick University, Casablanca, Morocco and a Master's degree in information systems and processing. She is a member of the research team "Automation, Electrical Systems and Renewable Energies" of the Hassania School of Public Works (EHTP). Her research work includes the integration of renewable energies in electrical networks.

Faissal El Mariami is a head of the research team "Electrical Networks and Static Converters". He is a Ph.D. and engineer which holds the University Research Habilitation (HDR). He is a Research Professor at National School of Electricity and Mechanics (ENSEM), Hassan II University, Casablanca, Morocco. His research interests include power system stability and smart grids.

Abdelaziz Belfqih is a head of the research team "Electrical Networks and Static Converters". He is a Ph.D. and engineer which holds the University Research Habilitation (HDR). He is a Research Professor at National School of Electricity and Mechanics (ENSEM), Hassan II University, Casablanca, Morocco. His research interests include electrical networks and smart grids.