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DIRECTIONAL OVERCURRENT RELAY COORDINATION IN A DISTRIBUTION SYSTEM USING GENETIC ALGORITHMS

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***Abstract* - The distribution systems protection plays a fundamental role in ensuring safe and reliable supply of electrical energy. An important point of the protection schemes consists of the relays coordination, which defines priorities in the operation time of these devices, since in the occurrence of a fault, the relays must act in order to keep the smallest portion of the system off. However, in the case of systems which has many protection devices, the task of coordinating the relays becomes complicated to perform analytically. For this reason, this paper presented a methodology based on Genetic Algorithms with the purpose of coordinating directional overcurrent relay in a distribution system. Finally, according to the developed methodology, it was possible to minimize the objective function effectively, obtaining a minimum value of 2.61 seconds in the 573th generation.**

***Keywords* - Distribution System, Genetic Algorithms, Optimization, Protection.**

I. INTRODUCTION

The electric power system is defined by the set of related electrical circuits, which consists of the generation, transmission and distribution of electric energy. In the distribution systems, it should be emphasized that the evaluation of the energy quality is established by a set of indicators, where the level of continuity and reliability are one of the most important indicators [1]. This is because, in practice, consumers are subject to interruptions in power supply due to failures, also called disturbances, and the execution of preventive maintenance services in the network [2]. Among the various types of disturbances that can occur in an electric power system, faults are considered to be one of the most relevant.

Faults consist in unplanned disconnections of the electric power system components and can be caused by a variety of situations, such as: weather conditions, equipment failures, accidents, vandalism, among others. The faults are classified as being symmetric and asymmetric fault (line-to-line, line-to-ground or double line-to-ground). In this context the protection system has the function of detecting and removing from service the equipment under fault conditions [3]. A scheme of protection of electrical systems has the following objectives:

- Protect the electric power system in order to maintain the electricity supply continuity;
- Avoid or minimize damages and costs of corrective maintenance (equipment repair);
- Ensure the physical integrity of the people involved, for example: operators and consumers of the electric power system.

It should be noted that in an electric power system there are several elements that must be protected by the power system protection. In order to achieve a good protection scheme for distribution lines, distance relays (DRs) are generally used together with directional overcurrent relays (DOCRs) [4]. Moreover, for a correct performance of this protection system, it is fundamental that all relays have adjustments that guarantee the coordination time interval. The problem of relay coordination consists in selecting the appropriate settings for each relay so that it can perform its function in order to ensure reliability, selectivity and continuity [5].

In this paper, the problem determining the optimum values of the time multiplier setting (TMS) and the pick-up current (Ip) of the DOCRs in a feeder with 13 nodes had been formulated using Genetic Algorithms (GA). Firstly, GA was used to coordinate six directional relays inserted into the analyzed feeder, then all constraints was verified to ensure that the GA was able to coordinate the relays correctly.

Section II of this paper illustrates the theory related to the relay coordination. Section III develops a detailed analysis of the GA. The case study of the feeder used in this paper is presented in Section IV. Section V shows the results and discussions related to the relays coordination. Finally, concluding remarks are provided in Section VI.

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II. COORDINATION OF OVERCURRENT RELAY IN DISTRIBUTION SYSTEMS

The relay coordination is a fundamental assignment and consists in defining the priorities for the power system protection performance, in other words, in the occurrence of a short-circuit, the coordinated relays will be able to remove the smallest possible portion of the electric system (selective protection). It should be noted that two devices in series are coordinated when: the closest device to the fault fails in its performance, then the second closest must actuate, respecting the coordination time interval.

The actuation time of the DOCR can be calculated using (1), where the higher the current value measured by relay, the shorter the actuation time of this relay [3, 6, 7].

$$T = TMS\left[\frac{A}{\left(\frac{I}{Ip}\right)^{P}-1}+B\right] \tag{1}$$

Where:

T	-	Actuation time of the DOCR.
TMS	-	Time multiplier setting.
I_p	-	Pick-up current.
A, B and P	-	Constants according to type of curve.

In this paper, the characteristic curve of the actuation time was the very inverse curve defined according to the International Electrotechnical Commission standard (IEC 60255-3, 1989) [8]. The constants A, B and P can be found in Table 1.

Table 1: Inverse time constants defined by IEC (IEC 60255-3, 1989).

Type of characteristics	A	P	B
Standard inverse	0.14	0.02	0.00
Very inverse	13.50	1.00	0.00
Extremely inverse	80.00	2.00	0.00

There is a need for coordination between DOCRs, and this task must be done in pairs. One of the DOCR will be the main protection, known as local protection ($DOCR_1$), and the other is the backup protection ($DOCR_2$). The coordination time interval between $DOCR_1$ and $DOCR_2$ is presented in (2).

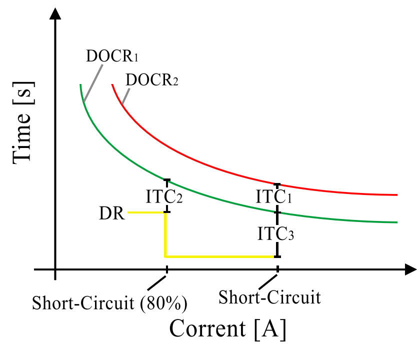
$$T_{DOCR2} - T_{DOCR1} \geq ITC_1 \tag{2}$$

Where:

T_{DOCR1}	-	Actuation time of the $DOCR_1$.
T_{DOCR2}	-	Actuation time of the $DOCR_2$.
ITC_1	-	Coordination time interval between $DOCR_1$ and $DOCR_2$.

In Figure 1, it is possible to observe the coordination scheme between DRs and DOCRs. The $DOCR_2$ operation time, in relation to the first DOCR, is defined as coordination time interval (ITC_1) and depends on the type of device: electromechanical relay or microprocessed relay. The first type has an ITC_1 interval between 0.3 and 0.4 s, and the second one, between 0.1 and 0.2 s [9]. Furthermore, the DOCR should only act after a waiting time of the DR performance, represented by ITC_2 and ITC_3. This timeout is the opening time of the circuit breaker plus a safety margin.

Figure 1: Coordination scheme between DR and DOCR [7].



Besides that, using (3) it is possible to calculate the minimum value of TMS.

$$TMS_{min} = \frac{T_{RDZ2}+ITC_2}{\frac{A}{\left(\frac{Icc_{80\%}}{Ip}\right)^{P}-1}+B} \tag{3}$$

Where:

TMS_{min}	-	Minimum TMS value.
T_{RDZ2}	-	Second zone protection time.
$Icc_{80\%}$	-	Short-circuit current for a fault at 80% of the main relay.
ITC_2	-	Coordination time interval between DR and $DOCR_1$ for a fault at 80%.

For correct coordination between the relays it is necessary to consider the constraints related to the actuation time of $DOCR_1$ for a fault at 80% of the main relay and the coordination time interval between DR and $DOCR_1$, presented in (4) and (5), respectively [10].

$$T_{DOCR_1 80\%} \geq T_{RDZ2} + ITC_2 \tag{4}$$

$$T_{DOCR_1} \geq ITC_3 \tag{5}$$

Where:

$T_{DOCR_1 80\%}$	-	Actuation time of $DOCR_1$ for a fault at 80% of the main relay.
ITC_3	-	Coordination time interval between DR and $DOCR_1$.

The objective function of the case study is represented by (6), which means the actuation times of all relays [11].

$$Minf = \sum_{i=1}^{n} T_n = T_1 + T_2 + T_3 + T_4 + T_4 + T_6 \tag{6}$$

Where:

$Minf$	-	Objective function.
T_n	-	Actuation times of each relay.

Furthermore, there are constraints that limit the values of TMS and Ip, presented in (7) and (8), respectively [11]. The lowest value of TMS (TMS_{min}) must be calculated using (3), while the maximum value of TMS is a specification of the protection device chosen, and in this paper, it was used one for the TMS_{max} value. In relation to the minimum pick-up current (Ip_{min}), it was used the highest charging current at the node where the relay was inserted, multiplied by an overload factor (20% for this case). Besides that, the maximum pick-up current (Ip_{max}) was determined as the smallest short-circuit current passing through the analyzed relay.

$$TMS_{min} \leq TMS_i \leq TMS_{max} \tag{7}$$

$$Ip_{min} \leq Ip_i \leq Ip_{max} \tag{8}$$

Where:

TMS_i	-	TMS value of relay R_i.
TMS_{max}	-	Maximum TMS value.
Ip_i	-	Ip value of relay R_i.
Ip_{min}	-	Minimum Ip value.
Ip_{max}	-	Maximum Ip value.

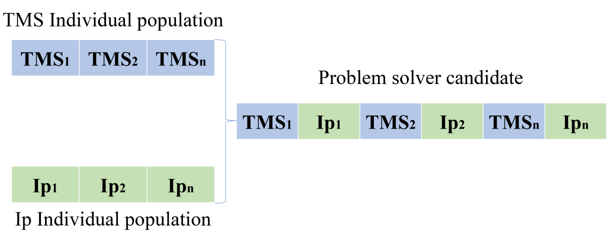
III. GENETIC ALGORITHMS

The GA is an Artificial Intelligence technique that is based on Darwin's natural selection theory to find solutions to optimization problems. The idea is to diversify population individuals who, at the end of the process, should be better adapted to the objective function and constraints [12, 13].

Moreover, an individual is a possible solution of the problem being characterized by a chromosome, which is a vector whose coordinates are the decision variables. The decision variables represents the genes of each individual and go through genetic operations at each iteration (or generation) of GA to generate new individuals with greater aptitude for the problem formulation. These operations are: selection, crossing, mutation and elitism [7, 14].

- Initial population: This is generated randomly. In this case there are two populations: one of "time multiplier settings" and one of "pick-up currents" (Figure 2).

Figure 2: GA mutation of a population individual [7].



- Objective function: In this step the individual is evaluated and receives a score referring to his ability to perform the objective function and constraints. In (9) the proposed evaluation function for this paper is described.

$$Minf = \sum_{i=1}^{n} T_n \tag{9}$$

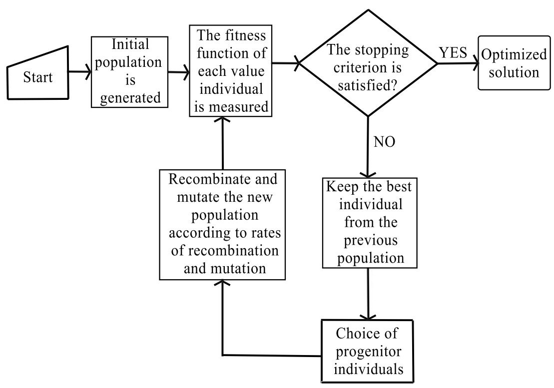
- Selection by tournament: Consists in selecting a series of individuals in the middle of the population, whose parameter is called tournament size (τ). Once selected, the two best individuals, will be chosen as parents in the crossing process, according to the objective function. This process is totally random and without any favoring to the choice within the population. The minimum value of τ is equal to 2, otherwise there will be no competition and if τ is equal to the number of individuals in the population, winners will always be the same, there being no genetic diversity [7, 15].

- Crossover operator: The crossover operator function is to exchange the genetic information to increase genetic diversity among population individuals [7, 15].

- Mutation operator: This genetic operator inserts variability in the population. The chromosome of a selected individual undergoes random changes, which guarantees the most comprehensive searching in the problem solution space. Thus, the mutation operator ensures that new genetic traits are introduced in the population that has not been presented in any individual of previous generations, providing a search algorithm [7, 15].

Figure 3 shows the flowchart of the GA proposed in this paper.

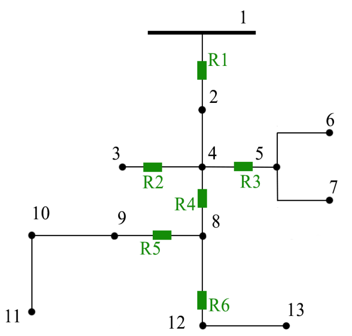
Figure 3: GA flowchart [7].



IV. CASE STUDY

In Figure 4 it is possible to observe the 13 node feeder used in this paper. It is worth noting that the loads present at the nodes are unbalanced, and this characteristic is common for the distribution systems. So, the proposal in this paper has a great applicability in real feeders. Additionally, the slack bus (node 1) was providing 13.8 kV to the feeder, which is a typical value for distribution systems in Brazil. It was inserted in this feeder six DOCRs which composes the power system protection, in order to protect all meshes of the circuit.

Figure 4: Feeder used in the case study.



Using Simulink software, the charging current values (Table 2) and the fault current values (Table 3) were obtained, based on the methodology presented in [16]. It should be noted that a fault was applied at the node where the short-circuit current was measured.

Table 2: Charging current.

Node	Charging current [A]		
	Phase A	Phase B	Phase C
1	493.51	384.60	420.92
2	493.41	384.60	420.92
3	24.49	19.40	19.02
4	412.27	307.37	352.09
5	48.66	46.16	45.25
6	17.91	14.74	18.02
7	23.14	21.05	20.64
8	410.88	305.08	349.04
9	116.82	51.98	68.07
10	68.90	51.97	38.56
11	29.83	30.64	30.05
12	134.94	93.73	115.98
13	72.74	29.28	54.79

Table 3: Fault current.

Node	Fault current [A]		
	Phase A	Phase B	Phase C
1	2648.69	2677.78	2665.95
2	2451.87	2484.24	2467.75
3	2353.24	2386.82	2368.84
4	2417.04	2452.64	2435.91
5	2353.73	2387.23	2369.16
6	2292.73	2324.31	2305.69
7	2292.42	2323.89	2305.16
8	2251.20	2284.64	2264.88
9	2215.70	2252.28	2231.75
10	2180.46	2220.64	2198.55
11	2145.53	2189.31	2165.82
12	2172.49	2204.34	2182.10
13	2139.11	2173.96	2151.03

Analyzing Table 2 and 3 it was possible to conclude that the load unbalance reflected in the loading currents, as expected. Table 4 shows the current value in the main relay and its respective backup devices, when a short-circuit is applied in the node in which the main relay is positioned. For example, in the third line, R3 is the main relay and R1 is the backup one, the fault current correspond to the current measured in R3 and R1 from a fault in the node that R3 is positioned. In addition, for the fault current value, it was used the highest fault current from each node.

Table 4: Fault current of each relay.

Main Relay	Fault Current	2nd Relay	Fault Current	3rd Relay	Fault Current
R1	2484.24^{F1}	-	-	-	-
R2	2386.82^{F2}	R1	2395.06^{F2}	-	-
R3	2387.23^{F3}	R1	2395.05^{F3}	-	-
R4	2284.64^{F4}	R1	2288.30^{F4}	-	-
R5	2252.28^{F5}	R4	2256.20^{F5}	R1	2260.99^{F5}
R6	2204.34^{F6}	R4	2209.15^{F6}	R1	2214.45^{F6}

Where F_n corresponds to the fault applied at the node where the R_n relay is inserted (For n=1,2,..,6).

As already pointed out, the relay settings have to respect some restrictions, which determines its maximum and minimum values. In Table 5 it was present the values of TMS_{min}, TMS_{max}, Ip_{min} and Ip_{max} for each relay.

Table 5: Constraints for the GA.

Relay	TMS_{min}	TMS_{max}	Ip_{min}[A]	Ip_{max}[A]
R1	0.23	1.00	592.21	2154.43
R2	0.22	1.00	29.38	2353.23
R3	0.22	1.00	58.39	2293.39
R4	0.21	1.00	493.05	2148.68
R5	0.20	1.00	140.18	2167.55
R6	0.20	1.00	161.92	2139.94

V. RESULTS AND DISCUSSION

It was considered microprocessed relays, with coordination interval of 0.2 s (ITC_1 = 0.2) and very inverse IEC curve in all relays used in the analyzed feeder. The second zone protection time, parameter was 0.3 s (T_{RDZ2} = 0.3), and for the other coordination interval times, ITC_2 and ITC_3 it were used 0.3 s and 0.2 s, respectively. In relation to the GA, the simulations were performed using 500 individuals, crossover rate of 60%, mutation rate of 30% and 800 was the maximum number of generations.

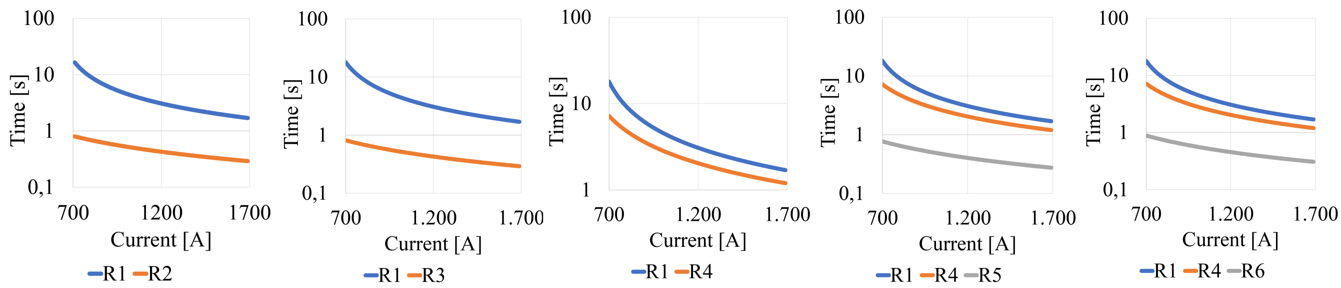
Then, using the constraints exposed before, the objective function and the input data of the analyzed feeder, it was possible to determine the values of TMS and Ip for each relay, by means of GA, as presented in Table 6.

Table 6: Output parameters of GA.

Relay	TMS	Ip [A]	Time [s]
R1	0.23	597	0.9822
R2	0.23	145	0.2008
R3	0.23	145	0.2008
R4	0.21	502	0.7983
R5	0.21	149	0.2008
R6	0.20	173	0.2299
Min f = 2.6130			
Generation=573			

Initially, it was noted that the values of Ip and TMS comply with the limits set forth in Table 5. Besides that, the difference between the operating time of the main relay in relation to the backup relay (in case of the main one fails) was obtained and exposed in the Table 7 for all cases. To reach Table 7, it was

Figure 5: Coordination time between the relays.



used the data presented in Table 4.

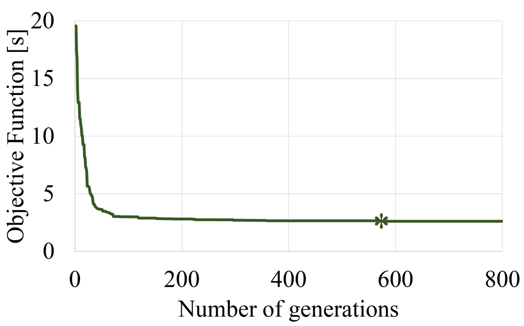
Table 7: Constraints tests.

Constraints	Time [s]
$T_1^{F_2}-T_2^{F_2} \geq 0.2$	0.8301
$T_1^{F_3}-T_3^{F_3} \geq 0.2$	0.8301
$T_1^{F_4}-T_4^{F_4} \geq 0.2$	0.2977
$T_4^{F_5}-T_5^{F_5} \geq 0.2$	0.6105
$T_1^{F_5}-T_4^{F_5} \geq 0.2$	0.3027
$T_4^{F_6}-T_6^{F_6} \geq 0.2$	0.6037
$T_1^{F_6}-T_4^{F_6} \geq 0.2$	0.3124

Analyzing Table 7 it is easy to conclude that the constraint related to the minimum value of ITC_1 was respected for all studied cases. Thus, in order to verify the coordination of the relays, the graphs present in Figure 5 were exposed.

Finally, in Figure 6 it is possible to see the evolution of the objective function, highlighting the optimal value achieved (in this case the optimal value was reached in the 573th generation). In this graph it is evident that the objective function decay as generations increase.

Figure 6: Evolution of GA.



VI. CONCLUSION

In this paper it was proposed a GA that was able to coordinate six directional overcurrent relays in a feeder with nine nodes. It is important to highlight that it was considered microprocessed relays, with coordination interval of 0.2 s (ITC_1 = 0.2) and very inverse IEC curve, however the methodology developed can be applied in any situation. Furthermore, this study is capable to be expanded to other kind of feeders (such as radial, parallel feeder, ring main and meshed system).

Analyzing the results it is possible to notice that the GA coordinated the six relays correctly, respecting all constraints. Moreover, knowing that the algorithms aimed to minimize the objective function, it was concluded that power protection system of this feeder must operate in order to maintain reliability, selectivity and continuity. Since the relays would actuate in the shortest possible time, isolating the smallest portion of the circuit.

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