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Optimal Setting of Protection Devices for Distribution Networks Connected to DG Using GWO

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ABSTRACT
This paper proposes a method to obtain the optimal settings of the protection scheme that is used to protect the distribution system in presence of distributed generation. The most common protection devices for the distribution systems are the overcurrent devices such as overcurrent relays, Auto-Reclosers (ARs) and fuses. The objective of the optimization process is to minimize the total operating time of the used protection devices. The objective is satisfied by determining the optimum pickup currents and the time dial settings for the protection devices. This provides faults isolation as fast as possible. The Grey Wolf Optimization (GWO) algorithm is applied in this paper to the proposed system to optimize the protection system parameters and eliminate any failure may be occurred to the protection scheme. The proposed method is applied on IEEE-13 node test system. The results obtained from the proposed method are compared with the results obtained without applying the optimization technique. The coordination failure cases are eliminated using those new settings proving the effectiveness of the proposed technique.
Keywords-GWO, distribution networks,distributed generation, Coordination.

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I. INTRODUCTION

The existing electrical distribution systems did not take into account the presence of Distributed Generators (DGs). Therefore, a need to address many incompatibility issues was arising. This puts great emphasis on the need to design and install new suitable protection schemes. The usual protection for the existing distribution systems is the Overcurrent protection (i.e. overcurrent relays, Auto-Reclosers (ARs) and fuses). When the DGs are connected to the distribution systems, their configurations are no more radial as there are contribution of fault currents from the DG's. This could lead to various issues like miss-operation of the fuses /relays considering temporary and permanent fault conditions [1]. So, the coordination between these devices is considered as one of the most important problems that need to be adjusted [2, 3].

Traditionally, the relays were coordinated in an upstream coordination scheme, with zones far from the substation to be isolated firstly, until the fault is cleared [4]. Protection under reach, sympathetic tripping, unsuccessful clearing of faults, and unplanned islanding cases are all key worries related directly to the deployment of DG systems [5-6]. Many utilities diminished these issues by strictly restraining the number, capacity, and placement of DG units [5]. Adaptive protection schemes were advised in [7-8]. These adaptive protection schemes are the results of microprocessors application in the area of protective relays and are growing in importance in the electrical power systems throughout the world.

Meta-heuristic optimization techniques are commonly used during the recent years. Many types of them such as Differential Evaluation (DE) [9], Genetic Algorithm (GA) [10-12], Ant Colony Optimization (ACO) [13], Particle Swarm Optimization (PSO) [14-16], Artificial Immune System (AIS) [17], Artificial Bee Colony (ABC) [18-19], Electromagnetic Field Optimization (EFO) [20], Invasive Weed Optimization (IWO) [21] and Ant Lion Optimizer (ALO) [22] and Pattern Search (PS) method [23] are used in coordination of protection devices in distribution systems. Ref. [9] optimized the settings of the overcurrent relays by using the continuous and discrete Differential Evaluation (DE) algorithm. Refs. [10-12] advised the GA to obtain the optimal relays coordination problem. Ref. [10-11] presented a new form of the optimization problem to determine the main and backup relays operating times by using GA. Ref. [12] determined the optimal setting of the relays by using the Nonlinear Linear Programming (NLP) and the GA methods. Ref. [14-16] used the PSO method to determine the optimal settings of the Direction Over-Currents relays (DOC). The ACO method was advised in [13] to calculate the optimal settings of the DOC relays. The applied objective function was to minimize the operation time of the relays. It took into consideration one fault type (SLG fault) at all buses and the backup relays operation time. Refs.

[18-19] applied the ABC method to determine the optimal settings of the over current relays in the distribution networks with DGs. The PS method was presented in [23] to calculate the optimal settings of the over current relays. Ref. [20] improved the EFO technique for obtaining the optimal settings of the direction over currents relays. Ref. [21] used the IWO technique to adapt the DOC relays coordination. Ref. [22] applied the ALO method to obtain the values of pickup currents and the time dial settings of the DOC to satisfy the minimum operating time.

The Grey wolf is one of wolves' species that belongs to "canidae family" (coyotes, dogs foxes, etc.). It is categorized as top hunters, that means, it dominates the top of the food chain. This hunter mainly prefers to live in groups. [24]. The Grey Wolf Optimizer (GWO) is found to be one of the best optimization meta-heuristic techniques. This gives a competitive result when comparing to other types of techniques which have the advantage of simplicity and flexibility for being applied in problems.

In this paper, the GWO is used as one of the optimization techniques to obtain the optimum protection scheme parameters. Moreover, it is applied to find out the best settings of the protection devices (i.e. delay time and pickup values). This is to satisfy the optimum case for the power system, optimum grading and operation sequence of the protection relays group by which a case of harmony can be obtained.

II. COORDINATION OF PROTECTION DEVICES PROBLEMS

The most protection devices used to protect the distribution networks are the overcurrent protection (overcurrent relay, AR and fuses). When two or more protection devices have a sequence of operation to isolate the fault, they are called coordinated with each other. The primary protection is responsible for operating first to disconnect the fault and is closer to the location of the fault. The backup relay works when the main relay failed to disconnect the fault. Following, the main points that can be taken when obtaining the coordination time between the fuses and the AR. Also, The effect of the DG sources integration on the coordination states between AR and fuses device.

2.1 Fuse- AR coordination

A distribution feeder connected to a load is illustrated in Fig. 1. This feeder is protected by AR and fuses. The fuses act against the permanent faults. While, the AR cuts-off the circuit breaker in fast-mode to allow the transient fault to be normalized. As a result, the fuse does not blow due to the transient faults, and the AR slow-mode will stay as fuse backup protection. Fig. 2 illustrates the AR and fuse coordination curve. The coordination between the AR and fuse is complex. The maximum and minimum fault currents is represented by the two vertical lines and the curves should be coordinated at these currents. The Maximum Clearing Time (MCT) curve is the upper curve while the Minimum Melting Time (MMT) curve is the lower one.

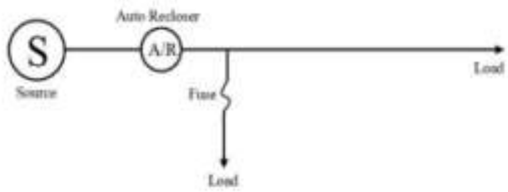

Fig.1: Distribution system with AR/Fuse

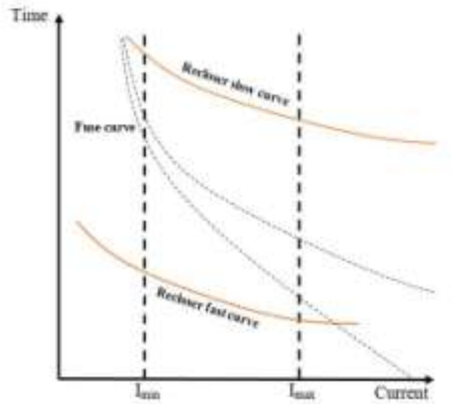

Fig. 2: AR and Fuse coordination curve

2.2 Fuse- AR coordination in present of DG

The effect of integration of the DG on the AR-Fuse coordination is illustrated in Fig. 3. The AR and the fuse currents are not the same. The Fuse current is greater than the AR current due to the current from the DG. This difference in fuse and AR current reduces the coordination margin. Fig. 4 illustrates the change in the fault currents with the MMT curve of the fuse and the fast mode curve of AR. The clearing feeder time and current without the DG is represented by black circles. In this case, the coordination margin should be suitable for the fast curve characteristic of the AR and the rating of the fuse.

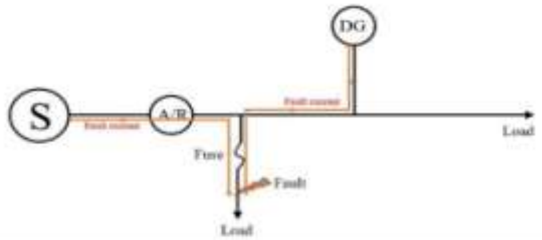

Fig. 3. Distribution system connected to DG with AR/Fuse

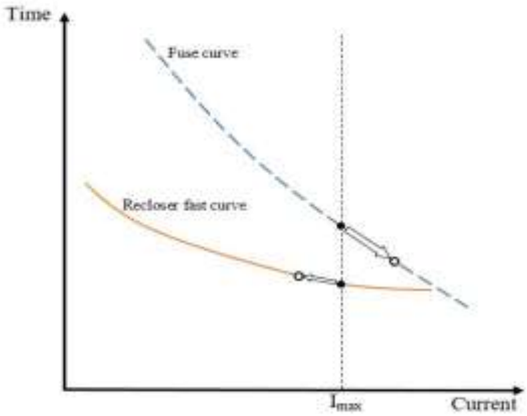

Fig. 4.DG impact on coordination of the AR fast mode and fuse

The clearing feeder time and current with the DG is represented by hollow circles. In this case, the MMT of the fuse is affected with current from the DG. The difference between the operating time of the AR and the fuse MMT is reduced, so the fuse can be blown. Also, the slow mode operation of the AR can be affected with the DG. Thus, the fuse operates faster than the AR that cause increase in the coordination margin. This increase is for the slow mode of the AR and can't be used for fast mode AR.

III. PROBLEM FORMULATION

The minimization of the total operating times of the protection devices in the Distribution Network is the objective of the optimization process. This satisfies the main function of the protection systems for disconnect the serious faults as quickly as possible. The following subsections illustrate the objective function and the constraints of the optimization problem.

3.1 Objective function

The proposed Objective Function (OF) is developed from [25] as shown in Eq. 1.

$$OF = \sum(T_m)^2 + \sum\left(\left(\left|\Delta T_{mb} - |\Delta T_{mb}|\right| * (T_m^2)\right) + \Delta Tmb+\Delta Tmb*Tm2)+\zeta(Tm-CI+Tm+CI)(1)$$

$$\forall\ \Delta T_{mb} = T_b - T_m - CI$$

where, T_m and T_b are the operating times of the main and backup protection in seconds. ΔT_{mb} is the difference time between the operating time of the main and backup relays. CI coordination interval constraint (0.3 second). ζ is the transient stability index.

The optimum settings of the protection devices are determined by using the OF. This is done by maintaining the time interval between all main and backup relays so that it does not exceed the allowable range for any fault in all protective relays.

3.2 Constraints

3.2.1 Relay's settings

The relays settings are concluded according to the minimum and maximum allowed currents. The minimum current is selected to be from 1.2 to 2 times of the normal current that passes in the relay. While the maximum setting for each relay is selected to be equal one third the fault current as represents in Eq. (2). The maximum and minimum values of the TDSs of the relays have a maximum and minimum values, which are described as Current-Time characteristic. The two parameters pickup current, I_P, and TDS are adopted during the optimization process.

$$I_{Pmin} \leq I_P \leq I_{Pmax} \quad (2)$$

$$TDS_{min} \leq TDS \leq TDS_{max} \quad (3)$$

where, I_{Pmin} and I_{Pmax} are the minimum and maximum pickup current. TDS_{min} and TDS_{max} are the minimum and maximum time dial setting.

For the same fault, the delay time of the main protection devices must be lesser than that of the backup. The Coordination Interval (CI) between the main and backup relays is based on the electric distribution company nature. The value of the CI is equals to the time of over travel, the operation time of circuit breaker and safety margin errors avoidance. The proper value of the CI is from 0.3 to 0.4 for electromechanical relays [26]. The Coordination Interval (CI) limit can be evaluated by,

$$T_b - T_m \geq TCI \quad (4)$$

The operating time of the relay is depended on the characteristics curve. It can be calculated by,

$$t = TDS * \left(\left(\frac{A}{(M^C - 1)}\right) + B \right) (5)$$

$$\forall M = \left({}^{I_f}/_{I_p} \right)$$

where, T_m and T_b are the operating time of the main and backup relays. I_f is the fault current. A, B and C are the constants that should be determined with respect to type of the OC relay characteristic. The standard values of these constants are listed in Table 1 [27].

Table 1. The constants of different types of DOCR characteristics

OCR Type	**A**	**B**	**C**
Standard Inverse	0.0515	0.114	0.02
Very Inverse	19.61	0.491	2
Extremely Inverse	28.2	0.1217	2

3.2.2 Transient stability

The instability may be occurred to the electric power system in case of exposing it to fault for a long time. The Critical Clearing Time (CCT) is defined as the maximum allowed time that the electric power system stability is ensured during the fault. The total operating times of the relays, t, should be lower than their related CCT. Thus, adding the CCT to the problem constraints ensures transient stability of the electric power systems. So, it should be integrated with the optimization problem. The CCT constraint is expressed by,

$t \leq CCT$ (6)

IV. THE PROPOSED OPTIMIZATION PROCEDURES

The optimal coordination of the DOC is obtained by; firstly, specify the combinations of each main and backup relays. Then, use the ETAP software to simulate the distribution network and the over-current relays. The values of the fault currents are measured by the main and backup relays at their protection zones. After that, the CI related to each couple of relays is set using the ETAP software. Finally, the proposed GWO technique is afterwards applied using the MATLAB software. Fig. 5 illustrates the flowchart for solving the optimization problem.

A process of two stages should be carried out, in order to obtain the optimal relay settings as shown in Fig. 5. First step (I), both the relay's pick-up current, I_P, and TDS parameters are considered to be continuous variables as the optimization formula. The CI of all relays combinations and the electric power system transient stability are tested by using the previously obtained setting.The relays that have an operating time greater than the deemed CI can be obtained with the Instantaneous Over Current (IOC) characteristics.

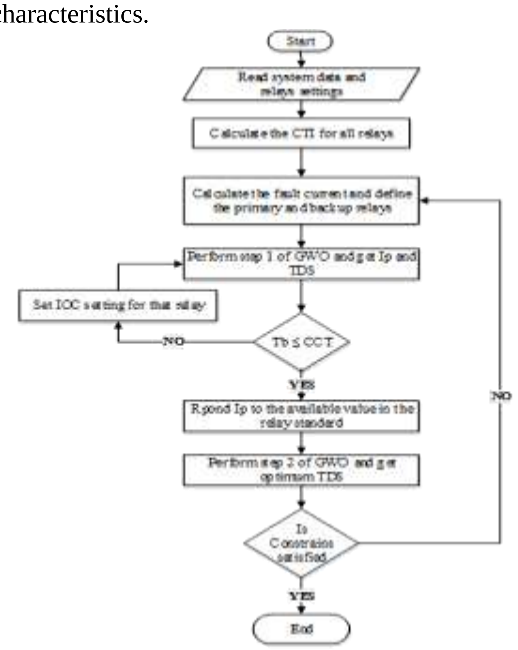

Fig. 5: Flowchart for performing GWO

In this case, the first step can be performed again to grant the optimal relay settings. In the second step (II), the pick-up current is adjusted to the closest available standard relay settings. In the case of all the constraints (relay and stability constraints) are satisfied, the optimization problem be finished successfully.

V. TEST SYSTEMS

The IEEE 13 nodes test feederis used to verify the applicability of the proposed methodology. It is considered as real systems with real simulation parameters for the cables, overhead transmission lines, transformers and loads. The simulation system is described and its results were verified and presented.

The test system is consisted of 13 nodes with voltage 4.16 kV that feed different types of loads through a combination of feeders and transmission lines as shown in Fig. 6. The protection system is composed of a main circuit breaker for the system which is controlled by an over current protection relay. There is an AR device between node 671 and 692, which is considered as an over current protection in its structure. It ensures the continuity of electric power in case of transient faults. At the end of each feeder there is a fuse to protect the loads. The eclectic loads are modeled as constant impedance (Z), constant power (PQ), or constant current (I) type. Table 2 in appendix lists the load data for the test system.

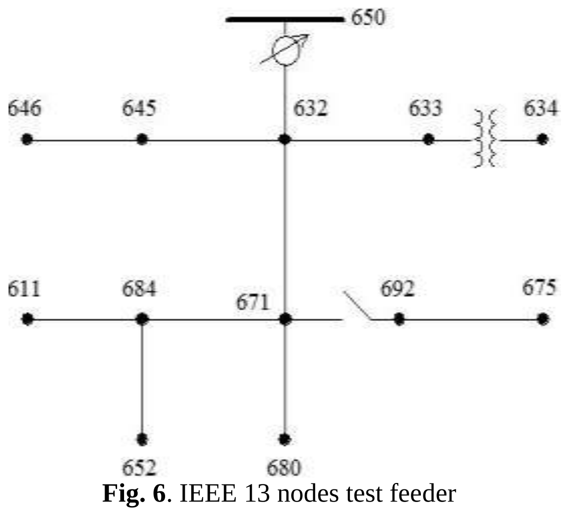

Fig. 6. IEEE 13 nodes test feeder

Table 2.IEEE 13 Node test feeder system spot load data.

Node	**Load**	**Ph-1**	**Ph-1**	**Ph-2**	**Ph-2**	**Ph-3**	**Ph-3**
Node	**Model**	**kW**	**kVAR**	**kW**	**kVAR**	**kW**	**kVAR**
634	**Y-PQ**	160	110	120	90	120	90
645	**Y-PQ**	0	0	170	125	0	0

646	**D-Z**	0	0	230	132	0	0
652	**Y-Z**	128	86	0	0	0	0
671	**D-PQ**	385	220	385	220	385	220
675	**Y-PQ**	485	190	68	60	290	212
692	**D-I**	0	0	0	0	170	151
611	**Y-I**	0	0	0	0	170	80
Total		**1158**	**606**	**973**	**627**	**1135**	**753**

The simulation study of the test systems is performed using ETAP then the results are validated. So, the systems are ready to test the transient and protection coordination issues. Moreover, the DGs with different capacities are connected under different conditions of fault cases in different locations through the distribution system to check if the protection system coordination would hold or lose its sequence and its reliability.

VI. RESULTS AND DISCUSSIONS

The main feeder protective devices are selected to be optimized and it has an AR installed on it. So, the AR is considered as the backup relay and the other relay downstream is considered the main one. By applying the proposed GWO optimization technique, the parameter λ in the OF is appointed to equal 10000 which represents the importance of the transient stability as recommended in [25]. The installed moderately inverse relays have the same characteristic types and follow the IEC 255-3 standard curves with parameters of 0.0515, 0.114 and 0.02 for A, B and C, respectively. The CI value is equal to 0.3 s between each backup and main relay as found from the real field experience. The minimum and maximum available tap of the relay's pickup currents are adopted to be from 0.5 and 5 in steps of 0.01. Moreover, the range of the relay's TDS parameter are selected from 0.01 to 1.2 in steps of 0.01. The CCT for faults downstream each relay is determined before initiating the optimal relay setting process. Hence, an advanced transient stability is performed to the system before perform the optimization process. The CCT is determined using the Transient Stability Study tool in the ETAP software and it is found to be 0.692 sec for the AR and 1.183 sec for the main relay.

By performing the GWO using the developed MATLAB code, the following results shown in Table 3 are obtained.

The fitness of the OF proposed in the GWO code in MATLAB software is shown in Fig. 7. It shows the fast response in finding the optimal settings for the relays.

Table 3. Protection devices settings for 13-Node IEEE system before/after GWO

Parameters	**Before Optimization**			**After Optimization**		
DG Capacity % of system Power	**30**	**40**	**50**	**30**	**40**	**50**
I_P(AR)	4.8	4.7	4.7	4.7	4.5	4.4
TDS (AR)	0.09	0.05	0.01	0.08	0.06	0.01
TDS (Relay)	1.1	1.2	1.2	0.9	1.1	1.1
Fuse F_1 (A)	18	18	18	25	25	18
Fuse F_2 (A)	35	35	35	45	35	35
Fuse F_3 (A)	140	140	140	150	150	140
Total Operating Time (Sec.)	**0.94**	**1.09**	**1.12**	**0.90**	**0.97**	**0.92**

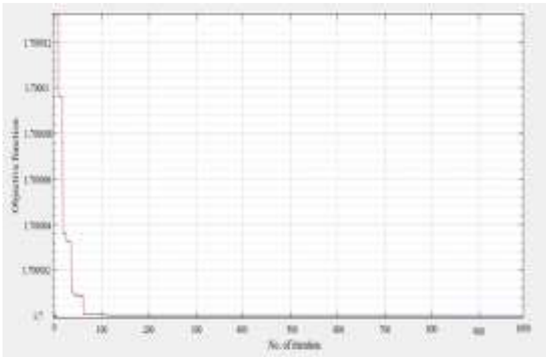

Fig. 7. Convergence of the objective function

Fig. 8 illustrates the state of setting balance and the correct sequence of operation of the main and backup relays in case of fault in the main feeder. These characteristics curves are simulated and verified using ETAP software. Also, the proposed constrain of CCT for each relay able to restore the stability state after it is subjected to three-phase fault in the main feeder as illustrated in Fig. 9. These curves in Fig. 9 are obtained from applying the transient stability analysis tool in the ETAP software.

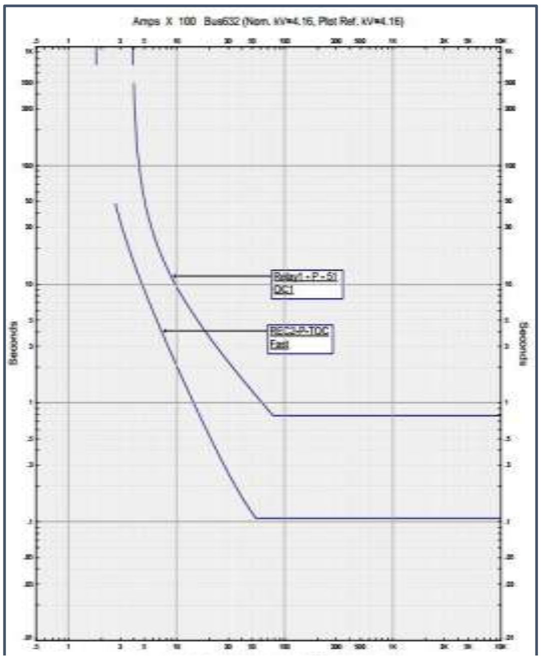

Fig. 8. Characteristics of main and backup relays

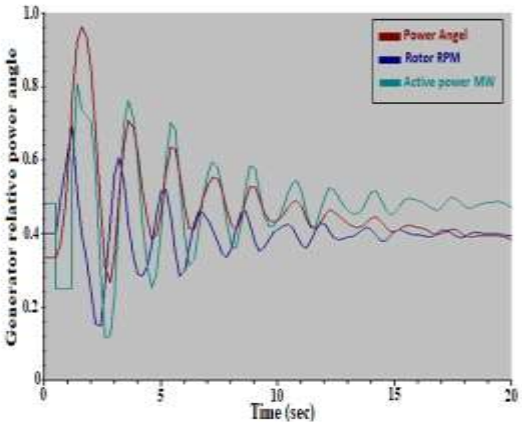

Fig. 9. Stability analysis for the system after using the settings

VII. CONCLUSION

Applying the proposed GWO optimization technique in this paper declares the benefit of shrinking the overall operating time of the overall protection system. The overall operating time of the protection system is the total time elapsed for the whole protection devices, which ends up by isolating the faulty zone. The CIs are satisfied which are the time difference between backup and main relays responses. In addition, the CCT for each protection device is taken in consideration and devices times are lower than its CCTs. This means that, the parameters of all relays are satisfied. Consequently, by executing the relay and stability constraints on the optimization procedures, a complete satisfying protection scheme on typical electricity distribution networks has been accomplished. Moreover, performing the optimization process using the proposed GWO optimization technique helped in refining the results and reducing the total time response of the protection system.

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