The Evolutionary Algorithm EPSO to Coordinate Directional Overcurrent Relays

Leite, H*; Barros, J*; Miranda, V*
*INESC Porto/ FE/UP, Portugal;
Office J205 – DEEC Faculdade de Engenharia da Universidade do Porto
Rua Roberto Frias s/n 4200-465 Porto, Portugal
email: hleite@fe.up.pt

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Abstract

The goal of this paper is to coordinate directional overcurrent relays using the Evolutionary Particle Swarm Optimization (EPSO) Algorithm. EPSO Algorithm has gained a lot of interest for its simplicity, robustness and easy implementation. Coordinate directional overcurrent relays on a meshed network deals with a large volume of data, with many calculations and constraints. So that, this work shows the viability of how EPSO algorithm can solve a non-linear coordination problem.

1 Introduction

The basic task of the overcurrent relays is to sense faults on the lines and to rapidly isolate these faults by opening all the current paths. This sensing and switching must occur as fast as possible to minimize damage. However, it should be very selective so no more of the network is removed from service than is necessary. In order to increase reliability, this need has led to the practice of providing both "primary" protection with "backup" protection which should function only if one of the primary devices fails. The primary protection system is designed for speed and the minimum network disruption while backup system operates more slowly (thereby giving the primary system a chance to operate). In order to have proper coordination of the primary and backup protective relays all the possible faults have to be accounted for. Each line has a variety of relays on each end. Typically there are both directional overcurrent relays for protection against phase faults on the line. The tripping time of the relay follows a time over current delayed curve, in which the time delay depends upon current. To design the time overcurrent curve two parameters are necessary: the pickup current tap setting (I_{pk}) and time dial setting or time multiplier setting (TMS, see Eq. 7). The settings should be designed for minimum relay time operation.

In general, the protective relay coordination problem is formulated as linear, nonlinear, or a mixed integer nonlinear programming problem depending on the type of variables in the problem. The pick-up current setting (I_{pk}, see Eq. 7)is the variable that determines the type of problem. If Ipk is fixed the problem becomes linear, if I_{pk} is a continuous variable the problem becomes a nonlinear programming and if I_{pk} assumes discrete values the problem becomes a mixed integer nonlinear programming problem [1,4].

In this work two approaches were used for finding the coordination. Considering I_{pk} fixed and therefore linear programming was used to find the TMS' setting. In the second approach I_{pk} was considered as a continuous variable and EPSO algorithm was used to find the optimal I_{pk} and TMS's settings. In order to determine the discrete relay setting I_{pk}, the value is rounding off from the continuous I_{pk} number obtained.

In summary, this work aim in to coordinate the overcurrent relays for all the possible fault occurrences onto the network and to make sure that the backup protection act after the failure of the primary protection. The EPSO Algorithm should give the settings for the overcurrent relays (I_{pk} and TMS, see Eq.7) when generation, load levels and network configuration change. So that, the algorithm should (i) review the system under current conditions for proper coordination of the relays; (ii) determine relay coordination requirements for possible permanent changes in the network; (iii) review relay operation as a part of post-fault analysis;

2 EPSO Algorithm: Outline

EPSO (Evolutionary Particle Swarm Optimization) is a population-based meta-heuristic, a variant of the self-adaptive Evolutionary Algorithms (EA) family, where the classical operators for recombination are replaced by a rule similar to the particle movement of Particle Swarm Optimization (PSO) [5,6]. Therefore, from a conceptual point of view, EPSO allows a double interpretation on how it works, because it may be seen from two perspectives: as a variant of PSO or as a variant of EA. This hybrid conception has the advantage of putting together positive characteristics of both methods.

The variables in an EPSO formulation are divided, according to the vocabulary used in the Evolution Strategies community, in object parameters (the X variables) and strategic parameters (the weights W).

At a given iteration, is considered a set of solutions or alternatives that will be called, as in PSO, *particles*. A particle is a set of object and strategic parameters [X, W]. The particle movement rule for EPSO is illustrated in Fig. 3 and governed by the following rule: at certain iteration k, given a particle $\boldsymbol{X}_i^{(k)}$, a new particle is generated at $\boldsymbol{X}_i^{(k+1)}$ by

$$\boldsymbol{X}_i^{(k+1)} = \boldsymbol{X}_i^{(k)} + \boldsymbol{V}_i^{(k+1)} \quad (1)$$

$$\boldsymbol{V}_i^{(k+1)} = Wi_i^* \boldsymbol{V}_i^{(k)} + Wm_i^* (\boldsymbol{b}_i - \boldsymbol{X}_i^{(k)}) + Wc_i^* \boldsymbol{P}(\boldsymbol{b}_G^* - \boldsymbol{X}_i^{(k)}) \quad (2)$$

$$\boldsymbol{V}_i^{(k)} = \boldsymbol{X}_i^{(k)} - \boldsymbol{X}_i^{(k-1)} \quad (3)$$

where:

- $\boldsymbol{b}_i$ – best point found so far by *i-th* particle;
- $\boldsymbol{b}_G$ – best point found so far by the swarm of particles ;
- $\boldsymbol{X}_i^{(k)}$ – particle *i*, in generation k;
- $\boldsymbol{V}_i^{(k)}$ – velocity of particle *i* in generation k;
- Wi_i – weight conditioning the inertia term (the particle tends to maintain previous movement);
- Wm_i – weight conditioning the memory term (the particle is attracted to its previous best position);
- Wc_i – weight conditioning the cooperation or information exchange term (the particle is attracted to the overall best-so far found by whole swarm);
- ***P*** – communication factor – a parameter that induces a stochastic star topology for the communication among particles. It is a diagonal matrix affecting all dimensions of a particle, containing binary variables of value 1 with probability *p* and value 0 with probability (1-*p*); thus, the *p* value controls the passage of information within the swarm.
- * – this symbol denotes that these variables undergo mutations.

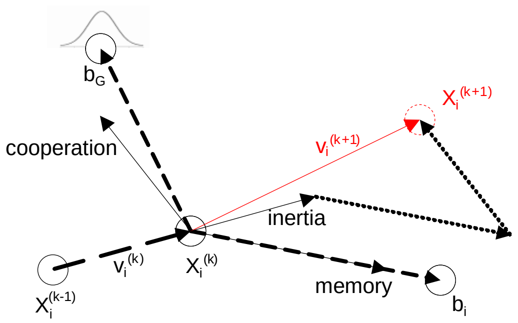

Fig. 3. Movement scheme of a particle (or individual) in EPSO [1].

The mutation schemes for the weights are usually lognormal or multiplicative normal, such as in

$$W^* = W(1 + \sigma N(0,1)) \quad (4)$$

where

- W – any parameter before mutation
- W* – parameter W after mutation
- N(0,1) – Gaussian distribution of 0 mean and standard deviation 1
- σ – mutation or learning rate

The global best b_g is also disturbed as in

$$\boldsymbol{b}_G^* = \boldsymbol{b}_G + Wg^* \boldsymbol{N}(0,1) \quad (5)$$

and the weight *Wg* is usually mutated according to a Gaussian additive scheme such as in

$$Wg^* = Wg + \sigma_g N(0,1) \quad (6)$$

where σ_g is a disturbance control parameter or a specific learning rate for this weight.

From an Evolutionary Algorithm point of view, EPSO is a self-adaptive evolutionary algorithm where the operation recombination is self-adaptive and expressed by the *particle movement* rule. This operator *particle movement* seems to be more effective than recombination randomly guided (as it traditionally is) in generating solutions that approach the optimum.

In terms of Particle Swarm Optimization interpretation, EPSO has self-adaptive characteristics, so it does not depend on external definition of weights – these will modify under the influence of selection to improve the search along the iterations. Because it is self-adaptive, EPSO seems to become more robust than PSO and more insensitive to parameter initialization [2]. In addition, EPSO modifies slightly the PSO concept, by defining a blurred target – Eq. (5) – for the global best instead of a single point, has also been demonstrated to improve the quality of the results.

In every algorithm step, each particle is replicated a certain number of times (usually once is enough). Afterwards, each replica of the particle has its strategic parameters (weights) mutated. All replicas and an original particle generate descendent particles through recombination, according to the particle movement rule described. The evaluation (calculation of fitness) of each descendant is followed by a selection procedure which ensures that the best offspring from each particle form a new generation.

By mutation and selection, the particles *learn* the values of their strategic parameters. Because the recombination operator is not neutral (the movement rule in PSO is enough to push particles to the zone of the optimum), this combined effect has a beneficial consequence in the discovery of the optimum.

3 Relay Coordination problem Formulation

As previously mentioned, directional earth overcurrent relays have two values to be set: the pick-up current (I_{pk}) and the time multiplier setting (TMS). Inverse time over current relays have an operating characteristic function of the type stated in equation (7).

$$t_{op} = \frac{K_1}{\left(\frac{I_{fault}}{I_{pk}}\right)^{K_2} + K_3} \times \mathrm{TMS}\ [s] \quad (7)$$

Where K_1, K_2 and K_3 are constants that depend on how inverse is the time characteristic of the overcurrent relays. Typical inverse time characteristics of these relays are standard inverse (SI), very inverse (VI) and extremely inverse (EI).

3.1 Mathematical Formulation

The directional earth overcurrent relays considered in this work have standard inverse (SI) time characteristic curve. According with the IEC standard: K_1= 0.14, K_2= 0.02 and K_3= -1in equation 7.

The directional earth overcurrent relay coordination problem is formulated mathematically as stated by constraints (8)-(11).

$$\min F = \sum_{os=1}^{OS}\sum_{i=1}^{m}\left(\sum_{j=0}^{n} t_{op\_backup_j} - t_{op\_primary_i} - CTI\right) \quad (8)$$

$$subject\ to:$$

$$\begin{cases} \left(t_{op\_backup_j}\right)_{os} - \left(t_{op\_primary_i}\right)_{os} \geq CTI & (9) \\ TMS_i \in \left[TMS_{i\min}; TMS_{i\max}\right] & (10) \\ I_{pk_i} \in \left[I_{earth_i}^{\min}; I_{fault_i}^{\min}\right] & (11) \end{cases}$$

$$\begin{cases} i = 1, \ldots, m \\ j = 0, \ldots, n \\ os = 1, \ldots, OS \end{cases}$$

Being:

$$t_{op\_primary_i} = \frac{0.14}{\left(\frac{I_{fault_{i\,primary}}}{I_{pk_i}}\right)^{0.02} - 1} \cdot TMS_i\ [s] \text{ and}$$

$$t_{op\_backup_j} = \frac{0.14}{\left(\frac{I_{fault_{j\,backup}}}{I_{pk_j}}\right)^{0.02} - 1} \cdot TMS_j\ [s].$$

Where i is the index of the vicinity of each of the *m* directional earth over current directional relays, j is the index of the backup relay(s) correspondent to the primary relay i, if they exist.

CTI is the coordination time interval between primary and backup relays. OS is the set of all network operating scenarios considered.

The minimum pick-up current setting is the minimum earth current $I_{earth_i}^{\min}$ acceptable for each relay to operate, see constraint (11). The maximum pick-up current setting is the minimum zero impedance single phase-to-ground fault current $I_{fault_i}^{\min}$ that is expected to flow through each relay. The zero impedance single phase-to-ground faults are simulated very near each primary relay. The decision variables are therefore the TMS and I_{pk} parameters of each directional earth over current directional relay, being thus this formulation a non-linear programming problem.

3.2 The Relay Coordination Problem as a Linear Programming (LP) Formulation

The mathematical formulation stated by constraints (8)-(11) can be regarded as a linear programming (LP) formulation if the parameter I_{pk} is fixed. The LP formulation considered is achieved by exchanging constraint (11) by constraint (12), maintaining the constraints (8)-(10).

$$I_{pk_i} = I_{earth_i}^{\min} \quad (12)$$

Constraint (12) assigns I_{pk} to be the minimum earth current acceptable for each relay to operate. The results obtained from the LP formulation will be compared with the ones derived from the non-linear formulation, solved by the EPSO-based relay coordination algorithm.

The EPSO-Based Relay Coordination Algorithm

The fitness *F* of each particle (*F_m* in the case of the mutated versions of both *TMS* and I_{pk} related populations) is evaluated according with the equation (13). Equation (13) is a rearrange of equation (8) with the purpose of leading the EPSO-based relay coordination algorithm to the feasible region of the decision space.

$$F = \left[\sum_{os=1}^{OS}\sum_{i=1}^{m}\left(\sum_{j=0}^{n} t_{op\_backup_j} - t_{op\_primary_i} - CTI\right)\right]_{t_{op\_backup_j} - t_{op\_primary_i} \geq CTI} + \left[M \cdot \sum k\right]_{t_{op\_backup_j} - t_{op\_primary_i} < CTI} \quad (13)$$

The index *k* counts the number of times the inequality coordination constraints are violated, i.e. the number of times a backup scheme is set to trigger earlier than the *CTI* in the case of a fault. This index *k* is then multiplied by a penalization factor, a very large constant *M*.

4 Relay Coordination in a Test Distribution System

The EPSO-based relay coordination algorithm has the purpose of setting the TMS and I_{pk} parameters of directional earth over current relays to achieve coordination under different network operating scenarios. A four-bus high-voltage distribution system is adopted in this study for validating the referred algorithm. The distribution system data is provided in Appendix A. The time-current inverse curve used was the standard inverse curve with the IEC characteristic (i.e., with K_1= 0.14, K_2= 0.02 and K_3= -1, see equation (7)). *CTI* is assumed to be 0.3 seconds. Both *TMS* and I_{pk} parameters can range continuously.

4.1 Different Network Operating Scenarios Considered

Fig. 1 shows the HV network considered with the two infeed network supply. Fig is the normal Operation Scenario (i.e. OS=1). However, two different configurations were considered. Operation Scenario 2(i.e. OS=2) where line 3 and 4 is out of order and the Operation Scenario 3 (i.e. OS=3) where the network is only supplied by G1.

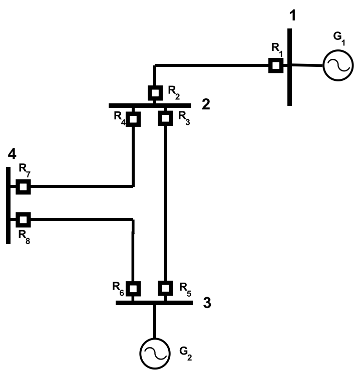

Fig. 1. Normal network operating scenario – *OS*= 1

Table 1 presents the primary/backup current relations in the operating Scenario 1(i.e. normal operation of the network). Single phase-to-ground faults are applied very near each primary relay.

Primary	*I (phase-ground) [kA]*	*Backup #1*	*I (phase-ground) [kA]*	*Backup #2*	*I (phase-ground) [kA]*
R1	3,7792	-		-	
R2	1,5678	R5	0,723	R7	0,8449
R3	2,8009	R7	0,8449	R1	1,9593
R4	2,6797	R5	0,723	R1	1,9593
R5	6,2692	R8	0,5923	-	
R6	6,1814	R3	0,5016	-	
R7	1,7869	R6	1,7869	-	
R8	1,01	R4	1,01	-	

Table 1: Primary/relation amps for OS=1

Table 2 presents the primary/backup current relations in the operating scenario 2 (i.e with line 3 and 4 out of order).

Primary	*I (phase-ground) [kA]*	*Backup #1*	*I (phase-ground) [kA]*	*Backup #2*	*I (phase-ground) [kA]*
R1	3,7886	-		-	
R2	0,8562	R5	0,8562	R7	0
R3	1,9695	R7	0	R1	1,9695
R4	2,8197	R5	0,8562	R1	1,9695
R5	5,716	R8	0	-	
R6	0	R3	0	-	
R7	0	-		-	
R8	0	R4	0	-	

Table 2 Primary/backup amps for OS=2

Table 3 presents the currents flowing through the relays when earth faults are applied and only the generator G_1 is available, i.e. the generator G_2 is out of order –OS= 3.

Primary	*I (phase-ground) [kA]*	*Backup #1*	*I (phase-ground) [kA]*	*Backup #2*	*I (phase-ground) [kA]*
R1	3,7809	-		-	
R2	0	R5	0	R7	0
R3	1,9586	R7	0	R1	1,9586
R4	1,9586	R5	0	R1	1,9586
R5	0,552	R8	0,552	-	
R6	0,4723	R3	0,4723	-	
R7	0,3122	R6	0,3122	-	
R8	0,8325	R4	0,8325	-	

Table 3 Primary/backup amps for OS=3

4.2 Relay Coordination: LP Formulation with Fixed I_{pk}

The LP formulation described by constraints (8)-(10) and (12) is applied to the test HV Network with the I_{pk} pre-set as 160A. Simplex algorithm was used in the LP formulation. The derived TMS setting follows in Table 4.

Relay	$X_{best} \equiv TMS_{opt}$
R1	0,639786
R2	0,305965
R3	0,529452
R4	0,529702
R5	0,379070
R6	0,482556
R7	0,376603
R8	0,432806

Table 4: TMS parameter for each directional earth over current relay

The fitness value *F* given by equation (8) was 5.8159.

4.3 **Relay Coordination: EPSO-based Algorithm**

The EPSO-based relay coordination algorithm sets both TMS and I_{pk} parameters of the directional earth over current relays to achieve coordination under different network operating scenarios, according with the constraints (9)-(11) and (13).

The EPSO characteristic parameters adopted in this study are provided in Appendix B. The *TMS* and I_{pk} parameters obtained with the EPSO-based relay coordination algorithm are presented in Table 5.

Relay	$X_{best} \equiv TMS_{opt}$	$X\_IPK_{best} \equiv I_{pk_{opt}}$ $[kA]$
R1	0,515329	0,160012
R2	0,179225	0,235296
R3	0,296972	0,257148
R4	0,345629	0,229449
R5	0,306761	0,160000
R6	0,483850	0,160002
R7	0,244947	0,217569
R8	0,330831	0,177168

Table 5: TMS and I_{pk} for the earth directional overcurrent relay obtained by the EPSO-based Algorithm

With the parameters obtained for I_{pk} and TMS detailed in Table 8, the fitness value *F* given by equation (13) is 5.0591.

4 Discussion

This paper presents two problem formulations for directional overcurrent relay coordination. A problem formulation for coordinating directional overcurrent relays based on the EPSO algorithm was proposed.

The EPSO-based algorithm is successfully applied to a test HV distribution system comprising many non-linear constraints, showing its ability to roam the search space towards the feasible set region. The results obtained from the EPSO-based algorithm shown superior quality compared with the ones provided by the LP formulation, i.e. with the pre-set fixed I_{pk} values (i.e comparing the fitness value *F*).

However, the output TMS and I_{pk} from the EPSO-algorithm are continuous values. The integer solution of the TMS and I_{pk} relay parameters are obtained by rounding off continuous values which could not be the optimal integer solution.

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Appendix

A – Distribution System Data

LINE DATA

	Resistance (Ω/km)	Reactance (Ω/km)	Zero Sequence Resistance R_0 (Ω/km)	Zero Sequence Resistance X_0 (Ω/km)	Length (km)
Line 1-2	1.385	4.802	3.925	15.545	12.67
Line 2-3	6.930	19.026	16.661	59.941	48.46
Line 2-4	3.774	9.545	8.656	30.172	24.35
Line 3-4	1.947	5.554	7.935	28.914	27.23

GENERATOR DATA

	Rated Power (MVA)	Rated Voltage (kV)	Power Factor	Subtransient Reactance X''_d (Ω)	Zero Sequence Impedance X_0 (Ω)
G1	100	60	1	5.349	16.788
G2	90	63	1	3.997	10.104

B – EPSO Characteristic Parameters

- Maximum number of iterations: *itmax* = 10000
- Number of particles: $N = 15$
- Dimension of the problem ≡ number of relays to be tuned: D= 8
- Noise rate to disturb the global best ($\boldsymbol{b}_G$): $\sigma_G = 0.001$
- Strategic parameters mutation ratio: $\sigma = 0.1$
- Communication factor conditioning matrix $\boldsymbol{P}$: $p = 0.2$
- Upper bound velocity of the particles: $V_{max} = X_{max} \times 0.1$
- Lower bound velocity of the particles: $V_{min} = -X_{max} \times 0.1$