APPLICATION OF A METHODOLOGY BASED ON EVOLUTIONARY PARTICLE SWARM OPTIMIZATION TO PROTECTION COORDINATION

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ABSTRACT

This paper describes the application of a discrete Evolutionary Particle Swarm Optimization-based (EPSO) methodology to a real case study network with high penetration of generation, for protection coordination. The high-resistance earth fault detection is based on the operation of a directional earth-fault overcurrent protection scheme with inverse time characteristic. The network is part of the HV Portuguese Distribution Network.

INTRODUCTION

The basic role of a protection system is to sense faults on lines or substations and to rapidly isolate these faults by opening all incoming currents paths. The action of detecting and switching must occur as fast as possible to minimize damage. However, it should be very selective so that no unnecessary network is removed from the service and thus disrupts as few customers as possible. As the issue of eliminating faults is of great importance, this task has to be very reliable. This need has led to the practice of providing “primary” protection with “backup” protection, which should function only when one of the primary device fails. The primary protection system is designed for speed and minimum network disruption while the backup system operates more slowly (giving the primary system a change to operate) and generally affects a larger portion of the network. Quality of Service requirements can lead Network Operators to explore HV Distribution Networks with multiple in-feed transmission feeders. Network Operators have to meet the requirements of sensitivity, selectivity, reliability, and speed under different network contingencies, meshed or radial topologies, multiple transmission feed interconnections and generation spread into the network. In this way, coordinating overcurrent relays becomes a challenge for the power systems protection engineers.
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. 1). 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. 1) is the variable that determines the type of problem. If I_{pk} 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]. EPSO has gained a lot of interest for its simplicity, robustness and easy implementation for resolving non-linear optimization problems. The coordination of directional earth-fault over current relies on a meshed network with high penetration of DG and represents a large volume of data involved, as well as many non-linear constraints and calculations.
The discrete EPSO based methodology aims to achieve an efficient coordination solution by setting the I_{pk} and TMS’s settings of each relay involved in the network. The discrete EPSO based methodology is built with the available off-line information of short-circuit earth currents and the minimum timescale between trip operation of primary and backup protection schemes.
In this paper it is assumed both time multiplier settings and pick-up currents may only assume discrete values, in accordance with the precision of most of the current digital protection devices. Therefore, the coordination methodology shall be envisaged as a non-linear integer optimization problem. The coordination methodology presented is based on the Evolutionary Particle Swarm Optimization (EPSO) methodology [5,6].

The coordination of Directional Inverse-time Earth Overcurrent Relays (DITEOCRs) on a meshed network with high penetration of DG represents a large volume of data involved, as well as many non-linear constraints and calculations. The EPSO-based methodology is validated on a real world case study network, part of the Portuguese HV distribution network. Multiple network operating topologies are considered in addition to the integration of DG. The high resistance earth fault detection is based on the operation of DITEOCRs with standard inverse time characteristic.

In this work, the mathematical formulation behind the coordination of DITEOCRs is presented, as well as the EPSO-based algorithm; followed by the results and the performance discussion of the application of the EPSO-based algorithm to a coordination of DITEOCRs from a HV Portuguese Distribution Network.

THE COORDINATION PROBLEM

Two values need to be set for DITEOCRs: the pick-up current (I_{pk}) and the time multiplier setting (TMS). DITEOCRs have an operating characteristic function of the type stated in equation (1).

$$\mathrm{t}_{op} = \frac{K_1}{\left(\frac{I_{fault}}{I_{pk}}\right)^{K_2} + K_3} \times \mathrm{TMS}\ [s] \qquad (1)$$

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

Mathematical Formulation

The DITEOCR coordination problem is formulated mathematically as stated by constraints (2) to (6). The relays considered have standard inverse (SI) time characteristic according with the IEC standard, being this way K_1= 0.14, K_2= 0.02 and K_3= -1.

$$\min F = \sum_{i=1}^{n} t_{op\_primary_i} \qquad (2)$$

$$subject \quad to:$$

$$\begin{cases} \left(t_{op\_backup_j}\right)\Big|_{os} - \left(t_{op\_primary_i}\right)\Big|_{os} \geq CTI & (3) \\ \left(t_{op\_backup_l}\right)\Big|_{os} - \left(t_{op\_primary_k}\right)\Big|_{os} \geq CTI & (4) \\ I_{pk_j}\Big|_{backup} \geq I_{pk_i}\Big|_{primary} & (5) \\ I_{pk_i} \in \left[I_{earth}^{\min}; I_{earth}^{\max}\right] & (6) \\ TMS_i \in \left[TMS_{i\min}; TMS_{i\max}\right] & (7) \end{cases}$$

$$\begin{cases} i = 1, ..., n \text{ primary relays} \\ j = 1, ..., m \text{ backup relays} \\ k = 1, ..., o \text{ primary relays} \\ l = 1, ..., p \text{ backup relays} \\ os = 1, ..., OS \text{ operating scenarios} \end{cases}$$

Being:

$$t_{op\_primary_{i/k}} = \frac{0.14}{\left(\frac{I_{fault_{i/k\,primary}}}{I_{pk_{i/k}}}\right)^{0.02} - 1} \cdot TMS_{i/k}\ [s] \text{ and}$$

$$t_{op\_backup_{j/l}} = \frac{0.14}{\left(\frac{I_{fault_{j/l_{backup}}}}{I_{pk_{j/l}}}\right)^{0.02} - 1} \cdot TMS_{j/l}\ [s].$$

Whereas i is the index of the primary relay nearer to an occurring single phase-to-ground short-circuit fault, j is the index of the backup relay(s) correspondent to the primary relay i, if they exist. k is the primary relay (if it exists) located further to the single phase-to-ground short-circuit fault occurred near primary relay i. l is the index of the backup relay(s) correspondent to the primary relay k, if they exist.

The objective function F orients solutions to minimize the sum of the operating times of all DITEOCR as primary relays, see equation (2). CTI is the coordination time interval, i.e. the minimum time required for the backup scheme to trigger in the case of the respective primary scheme does not come into action. Constraint (5) assures there is no zone for miscoordination between the primary and backup schemes, as the pick-up current(s) of the backup relay(s) is (are) always greater or equal than the pick-up current of the primary relay. The pick-up current setting is set between the minimum and the maximum earth current acceptable for the relays to operate, $I_{earth}^{\min}$ and $I_{earth}^{\max}$ respectively, see constraint (6). The decision variables are therefore the *TMS* and I_{pk} parameters of each DITEOCR, being this formulation a non-linear programming problem. Both *TMS* and I_{pk} are assumed to only range discretely.

The EPSO-based coordination methodology comprises three major steps. In the first step, it is defined a set of possible values for the I_{pk} setting of each DITEOCR. Following this, a Linear Programming (LP) formulation can be achieved. In the second step, a continuous LP tool is applied to obtain the *TMS* values associated with the I_{pk} values pre-set in the first step. The third and last step of the EPSO-based coordination methodology determines the "quasi-integer" *TMS* settings associated to the fittest continuous solution obtained in the second step. The "quasi-integer" term means the *TMS* values obtained have two decimal places.

THE EPSO-BASED RELAY COORDINATION ALGORITHM

At first, for each network operating scenario the primary/backup relations are identified. Then, zero impedance single phase-to-ground short-circuit faults are applied very near each relay. The earth currents flowing through all related primary/backup relays are obtained.

The closed loop of the EPSO-based coordination methodology starts with the initialization of the *X_IPK* and *X_IPK_m* populations (being the latter, with the *m* subscript, the *mutated* population). *X_IPK* and *X_IPK_m* are the I_{pk} related populations, being each particle a set of possible I_{pk} parameterizations for every DITEOCRs.

Based on the values pre-set for the I_{pk} variables, the non-linear relay coordination problem can now be regarded as a Linear Programming (LP) formulation. Therefore by solving the LP sub-problem for each particle the associated *TMS* variables, *X_TMS* (and *X_TMS_m* in the case of the *mutated* population), are acquired.

The fitness *F* (*F_m* in the case of the *mutated* version of the I_{pk} related population) of each particle is evaluated according to equation (8). Equation (8) is a rearrange of equation (2) with the purpose of leading the algorithm to the feasible region of the decision space.

$$\min F = \sum_{i=1}^{m} t_{op\_primary_i} + \left(M \cdot \sum k \right) \Bigg|_{\substack{t_{op\_backup_j} - t_{op\_primary_i} < CTI \\ I_{pk_j}|_{backup} < I_{pk_i}|_{primary}}} \quad (8)$$

In certain particles, depending on the I_{pk} parameters pre-set, the LP sub-problem does not converge. In these cases some of the inequality coordination constraints (represented by the constraints described by (4) and (5)) are violated. The index *k* counts the number of times the inequality coordination constraints are violated. This index *k* is then multiplied by a penalization factor, a very large constant *M*. Notice the EPSO-based coordination methodology only enters the penalization term if any primary/backup relation verifies

$t_{op\_backup_j} - t_{op\_primary_i} < CTI$ and/or $I_{pk_j}|_{backup} < I_{pk_i}|_{primary}$.

This way the coordination methodology is oriented to avoid non-feasible solutions minimizing the coordination time difference between backup and primary schemes.

PORTUGUESE HV DISTRIBUTION NETWORK : THE CASE STUDY

Fig. 1 shows the HV Distribution Network under test.

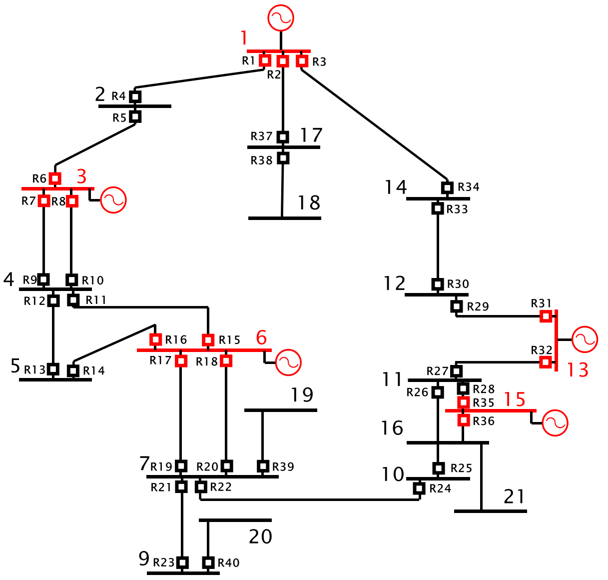

Fig. 1 HV Distribution Network under test

Busbars 1, 3, 6, 13 and 15 interconnect with the Portuguese transmission network. These interconnections are modelled by their respective maximum short circuit power ratio. The Portuguese transmission network has its backup protection upstream; therefore no backup scheme is required for the relays directly connected to the interconnecting busbars.

Both *TMS* and I_{pk} parameters are considered to take discrete values between the lower and upper bounds. The discrete step between consecutive *TMS* possible taps is 0.01 seconds. Possible I_{pk} values vary with a discrete step of 0.001 kA. The range for possible values of *TMS* is [0.05; 0.30] s and for I_{pk} is [0.080; 0.250] kA.

RELAY COORDINATION WITH THE EPSO-BASED COORDINATION ALGORITHM

The EPSO-based coordination methodology sets both *TMS* and I_{pk} parameters for achieving coordination in the protection system after a short-circuit fault, according to the constraints (3) to (8). This way the relay coordination problem may be resolved, as now the I_{pk} parameter can be parameterized along a defined range. The "quasi-integer" *TMS* values are achieved by a Branch-and-Bound based algorithm. The EPSO characteristic parameters are shown in Appendix A. The *TMS* and I_{pk} parameters obtained with the EPSO-based coordination methodology are presented in Table I.

TABLE I

TMS AND I_{PK} PARAMETERS FOR EACH OVER CURRENT RELAY OBTAINED WITH THE EPSO-BASED METHODOLOGY

Relay	*TMS [s]*	I_{pk} *[kA]*	***Relay***	*TMS [s]*	I_{pk} *[kA]*
R1	0.30	0.220	**R21**	0.15	0.242
R2	0.30	0.217	**R22**	0.14	0.250
R3	0.30	0.218	**R23**	1.50	0.220
R4	0.05	0.080	**R24**	0.05	0.250
R5	0.05	0.080	**R25**	0.05	0.250
R6	0.30	0.110	**R26**	0.05	0.250
R7	0.30	0.250	**R27**	0.05	0.127
R8	0.30	0.250	**R28**	0.05	0.103
R9	0.05	0.084	**R29**	0.05	0.080
R10	0.05	0.080	**R30**	0.06	0.233
R11	0.05	0.080	**R31**	0.30	0.249
R12	0.14	0.226	**R32**	0.30	0.250
R13	0.11	0.250	**R33**	0.15	0.080
R14	0.05	0.080	**R34**	0.05	0.080
R15	0.30	0.250	**R35**	0.30	0.250
R16	0.30	0.250	**R36**	0.30	0.250
R17	0.30	0.250	**R37**	1.50	0.092
R18	0.30	0.250	**R38**	0.05	0.080
R19	0.05	0.080	**R39**	0.05	0.080
R20	0.05	0.080	**R40**	0.05	0.080

The non-linear integer optimization problem is successfully resolved by means of the meta-heuristic methodology EPSO (Evolutionary Particle Swarm Optimization). The results obtained allow the setting of the DITEOCRs minimizing their operation time as primary relays, while respecting all coordination constraints, technical limits and network topologies.

CONCLUSION

In this paper we have introduced a new concept and demonstrated how, in practice, one may generate better solutions for protection coordination in a complex context. This complexity is not so much generated by the size of the network but more by the nature of the constraints involved, that limits or invalidates obvious options that could be suggested in a design-by-hand approach.

Our method is based on the use of a computational intelligence tool (a meta-heuristic denoted EPSO) to search for the best compromise solutions in a domain characterized by non-linear constraints and discrete solutions. Our development shows that this process is able to discover coordination solutions that are better than solutions proposed by experienced engineers, because of the non-linar optimization performed.

The case study presented, based on a real system, demonstrates that even when one cannot find a solution that completely satisfies all constraints in all scenarios, one is able to reduce to a minimum the number of events where full coordination is not possible to achieve. If these events are characterized by probabilities, the method can incorporate this and also come up with a coordination proposal that would minimize the probability of uncoordination events happening.

Therefore, the approach demonstrated in this paper constitutes a ready-made technique useful to improve the security of power system networks, and its principles are not limited to any particular or specific system. A general model and tool has therefore been developed, tested and made ready to be used in practice

Acknowledgments

The authors acknowledge the cooperation of the Laboratory of Systems Protection at DEEC/FEUP (University of Porto) and the financing support of the following FCT grants: PTDC/EEA-ENE/73829/2006. The authors also acknowledge the Portuguese Network Operator EDP Distribuição S.A.

REFERENCES

[1] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," Electric Power Systems Research, vol. 76, pp. 988-995, 2006.

[2] D. Vijayakumar and R. K. Nema, "Superiority of PSO Relay Coordination Algorithm over Non-Linear Programming: A Comparison, Review and Verification," in Power System Technology and IEEE Power India Conference, 2008. POWERCON 2008. Joint International Conference on, 2008, pp. 1-6.

[3] W. El-khattam and T. S. Sidhu, "Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study," Renewable Power Generation, IET, vol. 3, pp. 415-425, 2009.

[4] A. S. Noghabi, J. Sadeh, and H. R. Mashhadi, "Considering Different Network Topologies in Optimal Overcurrent Relay Coordination Using a Hybrid GA," Power Delivery, IEEE Transactions on, vol. 24, pp. 1857-1863, 2009.

[5] Miranda, V., Keko, H. and Jaramillo, A., EPSO: Evolutionary Particle Swarms, Advances in Evolutionary Computing for System Design, Book Chapter, ISBN 978-3-540-72376-9, Volume 66/2007, Springer Berlin / Heidelberg, July 2007.

[6] Miranda, V. and Fonseca, N., EPSO – Best-of-Two-Worlds Meta Heuristic Applied to Power System Problems, CEC '02 - Proceedings of the 2002 Congress on Evolutionary Computation, Vol. 2, pp. 1080 1085, Honolulu, USA, May 2002.

APPENDIX A

EPSO characteristic parameters

- Maximum number of iterations: 100
- Number of particles: 15
- Dimension of the problem (number of relays to be tuned): 40
- Noise rate to disturb the global best ($\boldsymbol{b}_G$): σ_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: $V_{min} = -X_{max} \times 0.1$