Article **Journal Electrical Engineering**
June 2021, Vol.5 No.14 1-8

Analysis of objective functions and weighting parameters syntonization for protection optimization

Análisis de funciones de aptitudes y sintonización de parámetros de pesos para la optimización de protecciones

SHIH, Meng Yen†*, LEZAMA-ZÁRRAGA, Francisco Román, CHAN-GONZALEZ, Jorge de Jesús and SALAZAR-UTIZ, Ricardo Rubén

Universidad Autónoma de Campeche, Campus V, Predio s/n por Av. Humberto Lanz Cardenas y Unidad Habitacional Ecologica Ambiental, Col. Ex-Hacienda Kala, CP 24085, San Francisco de Campeche, Cam., Mexico.

ID 1st Author: *Meng Yen, Shih* / **ORC ID:** 0000-0001-7475-6458, **CVU CONACYT ID:** 408617

ID 1st Co-author: *Francisco Román, Lezama-Zárraga* / **ORC ID:** 0000-0003-3397-7881, **Researcher ID Thomson:** U-1229-2018, **CVU CONACYT ID:** 205493

ID 2nd Co-author: *Jorge de Jesus, Chan-Gonzalez* / **ORC ID:** 0000-0002-8638-1646

ID 3rd Co-author: *Ricardo Rubén, Salazar-Utiz* / **ORC ID:** 0000-0003-2307-737X, **CVU CONACYT ID:** 416277

DOI: 10.35429/JEE.2021.14.5.1.8 Received January 10, 2021; Accepted June 30, 2021

Abstract

The protection coordination problem can be a very complicated task when dealing with meshed networks. Hence, many researchers have formulated the complex coordination problem as an optimization one. Different optimization methods have been proposed for solving the protection coordination problem. However, the different optimization methods are all sensitive to the objective function and the respective weighting parameters. A good optimization method suitable for certain task may not perform successfully if this optimization method does not have the appropriate objective function and/or syntonization of weighting parameters. Therefore, in this article, several proposed objective functions are analyzed and compared. Then the weighting parameters of the proposed objective function are syntonized. Genetic Algorithm is used as a heuristic searching motor for protection optimization. The objective function and the weighting parameters suit different optimization algorithms.

Genetic algorithm, Heuristic optimization, Objective function, Protection optimization, Weighting parameter syntonization

Resumen

El problema de coordinación de protección puede ser una tarea muy complicada cuando se trata de redes mallados. Por tanto, muchos investigadores han formulado el problema complicado de coordinación como un problema de optimización. Diferentes métodos de optimización han sido propuestos para resolver este problema. Sin embargo, todos los diferentes métodos de optimización son sensitivos ante la Función de Aptitud y los Parámetros de Pesos respectivos. Un buen método de optimización adecuado para cierta tarea puede que no ejecute exitosamente si este método no tiene la Función de Aptitud adecuada y/o los Parámetros de Pesos sintonizados. Por lo tanto, en este artículo, varias Funciones de Aptitudes son analizados y comparados. Además, los Parámetros de Pesos de la Función de Aptitud propuesto es sintonizado. El Algoritmo Genético es utilizado como el motor de búsqueda heurístico para la optimización de protección. La Función de Aptitud y los Parámetros de Pesos adapta para los diferentes algoritmos de optimización.

Algoritmo genético, Optimización heurístico, Función de aptitud, Optimización de protección, Sintonización de parámetros de pesos

Citation: SHIH, Meng Yen, LEZAMA-ZÁRRAGA, Francisco Román, CHAN-GONZALEZ, Jorge de Jesús and SALAZAR-UTIZ, Ricardo Rubén. Analysis of objective functions and weighting parameters syntonization for protection optimization. Journal Electrical Engineering. 2021. 5-14:1-8.

---

*Correspondence to Author (Email: smengyen@uacam.mx)
† Researcher contributing as first author.

Introduction

Protective devices play an important role in the electrical power system for safety, reliability, continuity, voltage quality, service life of primary equipment and life of personnel (Blackburn & Domin 2006). They operate and isolate the electrical network zone under disturbances and/or abnormal operations such as atmospheric discharges, faults caused by animals, accidental short circuits, improper personnel operations etc. (Blackburn & Domin 2006).

Of the different protection devices, the Directional Over Current Relay (DOCR) is widely used in sub-transmission and distribution lines due to its low cost and also offers the virtue of tolerating temporary overloads.

The DOCR has the principle of selective operation. Therefore, in order for the DOCRs to work together properly, they must be coordinated. Coordination states that the relay must provide primary protective operation with the minimum possible time when the fault is located within the protection zone and at the same time provide backup protective operation with a preset time delay when the fault is located in adjacent protection zone (Gers & Holmes 2011, Blackburn & Domin 2006). So, each line or element is protected by at least two protections, or, put another way, having overlapping protection zones.

The coordination of DOCRs is not an exact science, but as an Art it involves some degree of uncertainty due to its complexity, multiple local minima solutions and the use of heuristic optimization methods. So, it is difficult to claim that it has found optimal, but close to optimal, results.

Researchers have devoted their efforts in the study of the DOCR coordination problem, formulating it as an optimization problem and employing different optimization methods to attack this highly complex problem.

Justification

DOCR coordination has evolved from manual, software-assisted, and now heuristic optimization methods.

This evolution can be contributed by some reasons: the nature of the complex DOCRs coordination problem in meshed networks that as the electrical network under study is more meshed and larger, the coordination complexity will be higher (Gers & Holmes 2011); the time delay for performing the complex work manually (Gers & Holmes 2011); and the aspiration for better results that satisfies all DOCRs constraints to establish coordination between protection devices.

Some reported works are: Bedekar & Bhide (2011) proposes coordination of protections using Hybrid Genetic Algorithm (GA); Amraee (2012) proposes implementation of search engine algorithm for optimization of DOCRs; Srivastava, et al (2016) proposes optimization of protections using Particle Swarm (PSO); Saha, et al (2016) proposes computation of protections using teaching-learning based optimization (TLBO).

From the above described, it is aspired to solve the protection coordination problem using optimization methods. However, an appropriate fitness function and the respective suitable weight parameters need to be determined.

Objective

To evaluate the Suitability Functions and tune the weight parameters of the objective subfunctions to suit the GA search engine to solve the DOCRs coordination problem. To analyze and find the conclusion which of the Skill Functions performs better.

Hypothesis

By tuning the weights parameters of the proposed fitness function, it is possible to obtain adequate protection settings results and achieve minimum protection operation times for meshed systems. The proposal perhaps offers better results than the fitness functions proposed in the literatures.

Problem statement

The protections are required to provide primary and backup function with the same set of dial and pickup current settings. So, it is intentionally desired that there be overlapping protection zones.

This is illustrated in Figure 1. It is observed that line $\overline{BC}$ has overlapping protection zones where R1 provides primary operation and R2 provides backup operation for the same line $\overline{BC}$.

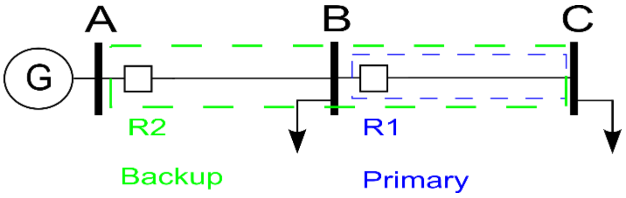

Figure 1 Overlaps of protection zones
Source: Own elaboration

DOCRs have an inverse time characteristic that is defined by the IEEE C37.112-1996 standard. This is presented in equation 1

$$t = \left[\frac{A}{\left(\frac{I_{scmax}}{I_p}\right)^n - 1} + B \right] * dial \qquad (1)$$

Where t is the DOCR operation time, I_{scmax} is the maximum fault current, I_p is the inrush current setting, dial is the curve family setting, and A, B, n are IEEE standard constants. In this study, the very inverse characteristic (VI) of IEEE standard is employed which has the values of 19.61, 0.491 and 2 of the constants A, B, n respectively.

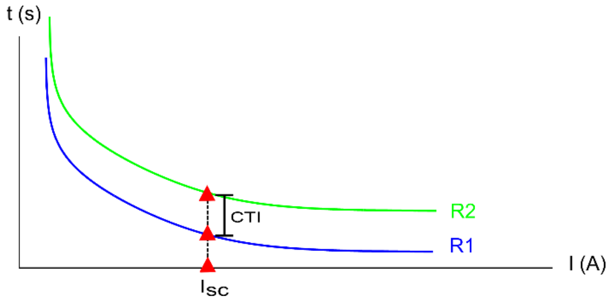

Figure 2 Coordinated primary and backup protection operation of relays R1 and R2
Source: Own elaboration

The operation curves and characteristics of the coordinated relays R1 and R2 are presented in Figure 2. It is observed that they have a coordination time interval (CTI) between them for a given fault current magnitude. In this time-current plane, the horizontal axis represents the current magnitudes in amperes and the vertical axis represents the operating time of the DOCRs in seconds.

Problem suitability functions for optimizing protection settings using genetic algorithm

To optimize the coordination problem and obtain results close to the global optimum, the following conditions must be met: optimization method, a suitable fitness function f(x) and properly tuning the weights of each fitness subfunction.

In this work, we use the GA which is a well recognized algorithm in the computer area for several decades to perform the analysis between the different fitness functions and the proposal. It is also used to tune the weights parameters of the proposed fitness function. The flowchart for the optimization of protections using GA is presented in Figure 3.

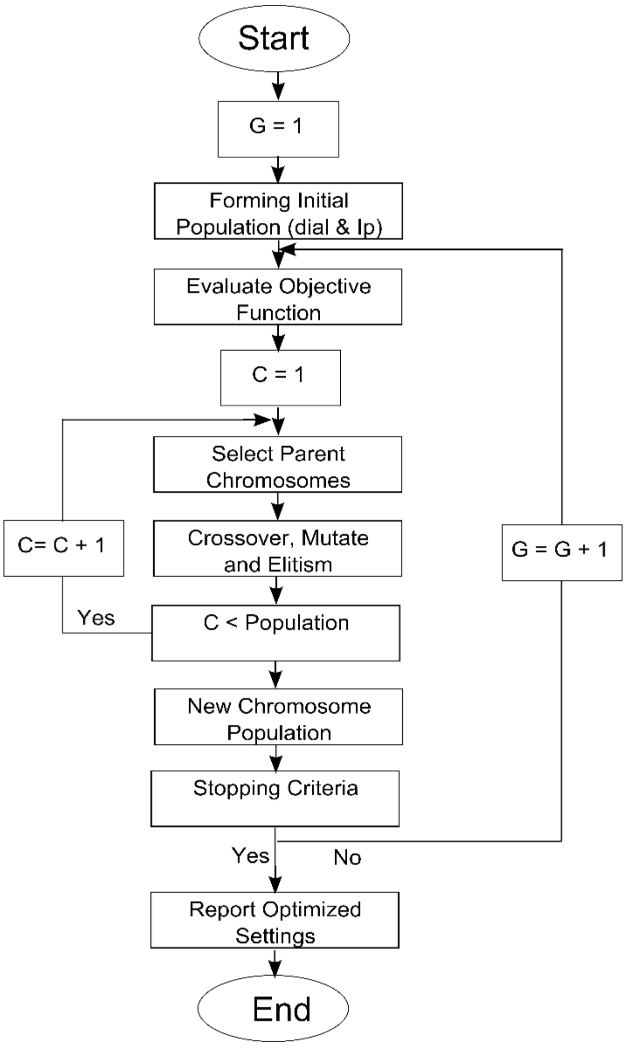

Figure 3 Protection optimization flowchart using GA
Source: Own elaboration

The following table presents the Skills Functions to be studied, both from literatures and the one proposed in this work, in Table 1.

	f(x)	Method	Literatures
I	$\sum_{j=1}^{m} t_{p,j}$	GA, PSO	Zeineldin, et al (2006); Mansour, et al (2007); Bedekar & Bhide (2011); Bedekar & Bhide (2011); Alam, et al (2015).
II	$\sum_{j=1}^{m} t_{p,j} + \sum_{j=1}^{m} t_{b,j}$	TLBO	Saha, et al (2016); Kalage, et al (2016).
III	$\left(\frac{MC}{P}\right) + \alpha\left(\frac{\sum_{j=1}^{P} t_{p,j}}{P}\right) + \beta\left(\frac{\sum_{j=1}^{P} t_{b,j}}{P}\right) + \delta\left(\sum_{L=1}^{P} E_{CTI_L}\right)$	GA	Proposal

Table 1 Skills functions
Source: Own elaboration

The fitness functions of the literatures consist of the summation of primary operation times and backups. While the proposed fitness function has the evaluation of the number of coordination violations, and the Coordination Time Interval (CTI) errors added to the fitness functions in the literatures. Which offers better optimization results.

The parameters: α, β, δ represent the weights affecting each fitness subfunction. MC is the number of coordination losses, P is the number of coordination pairs, t_p is the primary operation time, t_b is the backup operation time, and E_{CTI} is the coordination pair CTI error.

The CTI constraint for selective coordination of protections is expressed mathematically in equation 2:

$$t_b = t_p + CTI \tag{2}$$

The upper and lower bounds of the relay settings in equations 3 and 4 are also presented as optimization constraints:

$$\text{dial}_{\text{min}} \leq \text{dial} \leq \text{dial}_{\text{max}} \tag{3}$$

$$I_{p_{min}} \leq I_p \leq min(I_{sc_{min}}, I_{p_{max}}) \tag{4}$$

Simulation parameters and test systems

In Table 2, the parameters to perform the optimization of protections employing GA and the complexity of the test system are listed. Where the weights parameters δ, τ and ρ will be defined based on the results obtained from weights analysis of the proposed fitness function observing the Pareto Frontier. The number of constraints is the total sum of CTI, $dial$ and I_p.

Parameters	Values
CTI	0.3
dial	[0.05:2.0]
Ip	[1.4:1.6]*Icarga
α, β, δ	To be defined, Pareto Frontiers analysis
Population	100
Generations	2,000
No. of lines	5
No. of DOCRs	10
No. of decision variables	20
No. of restrictions	36

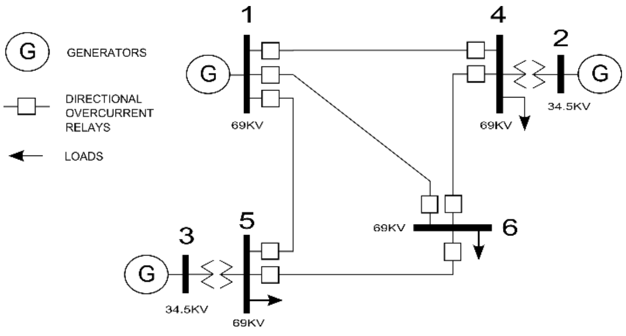

Figure 4 The 6-bus meshed test system
Source: Hadi Saadat, Power system analysis, McGraw-Hill, ISBN 0-07-561634-3, 1999

Table 3 shows the line parameters. Where R is the resistance, X is the reactance and 1/2B is the shunt admittance.

Bus	Bus	R	X	1/2 B
1	4	0.035	0.225	0.0065
1	5	0.025	0.105	0.0045
1	6	0.040	0.215	0.0055
2	4	0.000	0.035	0.0000
3	5	0.000	0.042	0.0000
4	6	0.028	0.125	0.0035
5	6	0.026	0.175	0.0300

Table 3 Line parameters
Source: Hadi Saadat, Power system analysis, McGraw-Hill, ISBN 0-07-561634-3, 1999.

Table 4 shows the parameters of transient reactance, voltage, active and reactive powers of generations and loads.

Bus	Generation					Charge	
	X'd	V	MW	Limites Mvar		MW	Mvar
				Min	Max		
1	0.20	1.060					
2	0.15	1.040	50	0	40		
3	0.25	1.030	30	0	20		
4						100	70
5						30	5
6						20	5

Table 4 Slightly modified generator and load parameters
Source: Hadi Saadat, Power system analysis, McGraw-Hill, ISBN 0-07-561634-3, 1999

The IEEE 14-bus system will be used for the analysis and tuning of proposed fitness function weights and the topology is presented in Figure 5. The system is an approximation of American Electric Power System in February 1962 consisting of 14 buses, 5 generators and 11 loads.

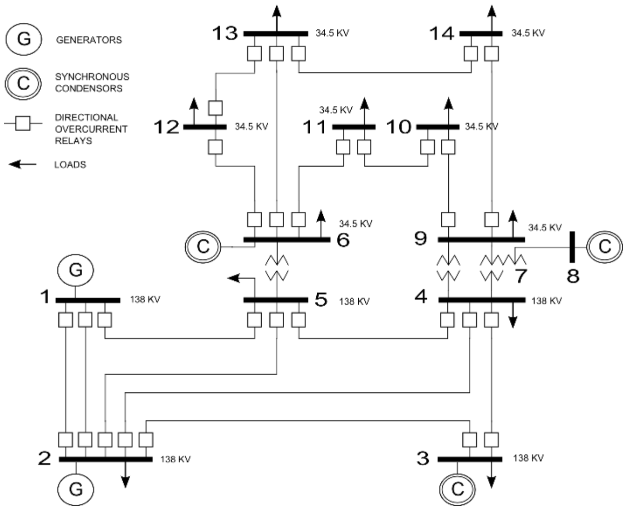

Figure 5 The IEEE 14 bus test system
Source:http://labs.ece.uw.edu/pstca/pf14/pg_tca14bus.htm

The line parameters, as well as the transient reactance's of generators, voltages, active and reactive powers of generations and loads are standardized data and can be found at (http://labs.ece.uw.edu/pstca/pf14/pg_tca14bus.htm).

It is worth mentioning that slight modifications were made for both systems in order to adapt the transmission system to the sub-transmission voltage level where the relay protection principle under study is implemented.

Simulations and results

In Table 5, the tuning results of the weights (α, β and δ) of the proposed fitness function are presented.

The weights parameters α, β and δ are evaluated between the interval [0.25:0.25:2]. Therefore, it has a total of 512 combinations. Each combination was evaluated in 50 simulations of the IEEE 14-bus system meshed over 2,000 generations. Subsequently, the average fitness function, the number of coordination losses and their respective standard deviations, as well as the averaged primary operation times, backups and CTIs are presented in Table 5, but to save space, only the best tuning combinations are presented, from which plot the Pareto Frontier plots presented in Figures 6, 7 and 8.

It can be observed from Figure 6, that the minimum primary operation time occurs when the weight parameter α increases up to 2. Which reveals that the best tuning for the weight parameter α is 2.

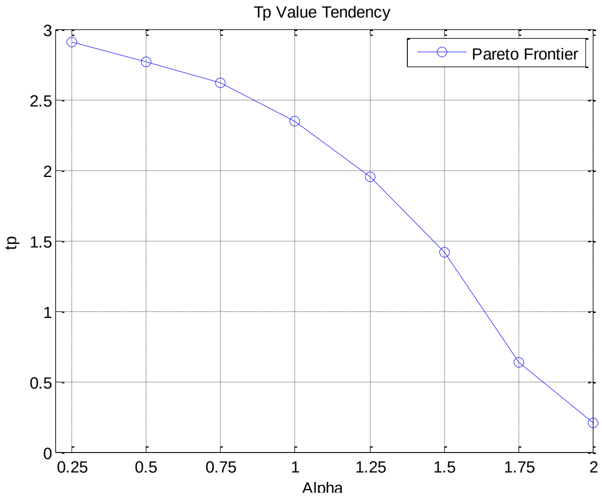

Figure 6 Pareto frontier of the weight parameter α and the trend of primary operation time
Source: Own elaboration

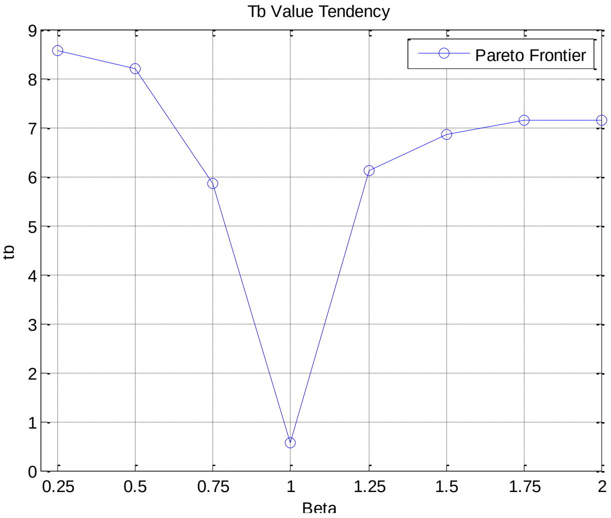

Figure 7 Pareto frontier of the weight parameter β and the trend of the operating time backup
Source: Own elaboration

It can be observed from Figure 7, that the minimum backup operation time occurs when the weight parameter β is located at the value 1. Which reveals that the best tuning for the weight parameter β is 1.

	α	β	δ	f(x)	f(x)-SD	MC	MC-SD	tp	tb	CTI
tp	**0.25**	1	2	8.71	0.72	0.00	0.00	**2.91**	7.90	5.00
	0.5	1	2	9.04	0.62	0.00	0.00	**2.77**	7.58	4.81
	0.75	1	2	9.39	0.66	0.00	0.00	**2.62**	7.34	4.73
	1	1	2	9.05	0.76	0.00	0.00	**2.35**	6.63	4.28
	1.25	1	2	8.08	0.66	0.00	0.00	**1.95**	5.57	3.61
	1.5	1	2	6.22	0.69	0.00	0.00	**1.41**	4.02	2.61
	1.75	1	2	2.96	0.45	0.00	0.00	**0.64**	1.78	1.15
	2	1	2	0.98	0.01	0.00	0.00	**0.21**	0.56	0.36
tb	2	**0.25**	2	7.06	0.56	0.00	0.00	2.42	**8.56**	6.14
	2	**0.5**	2	9.22	0.79	0.00	0.00	2.52	**8.20**	5.68
	2	**0.75**	2	8.34	0.61	0.00	0.00	1.94	**5.86**	3.92
	2	**1**	2	0.98	0.01	0.00	0.00	0.21	**0.56**	0.36
	2	**1.25**	2	12.08	1.00	0.00	0.00	2.18	**6.12**	3.94
	2	**1.5**	2	15.16	1.29	0.00	0.00	2.40	**6.85**	4.45
	2	**1.75**	2	17.85	1.28	0.00	0.00	2.63	**7.16**	4.53
	2	**2**	2	19.67	1.74	0.00	0.00	2.65	**7.14**	4.49
CTI	2	1	**0.25**	11.89	6.73	0.00	0.00	2.34	7.21	**4.87**
	2	1	**0.5**	3.48	0.72	0.00	0.00	0.74	1.99	**1.25**
	2	1	**0.75**	2.18	0.28	0.00	0.00	0.46	1.25	**0.79**
	2	1	**1**	1.48	0.27	0.00	0.00	0.31	0.85	**0.54**
	2	1	**1.25**	1.25	0.16	0.00	0.00	0.26	0.72	**0.46**
	2	1	**1.5**	1.10	0.14	0.00	0.00	0.23	0.63	**0.41**
	2	1	**1.75**	1.02	0.04	0.00	0.00	0.21	0.59	**0.38**
	2	1	**2**	0.98	0.01	0.00	0.00	0.21	0.56	**0.36**

Table 5 Parameter tuning of weights α, β and δ, for optimization
Source: Own elaboration

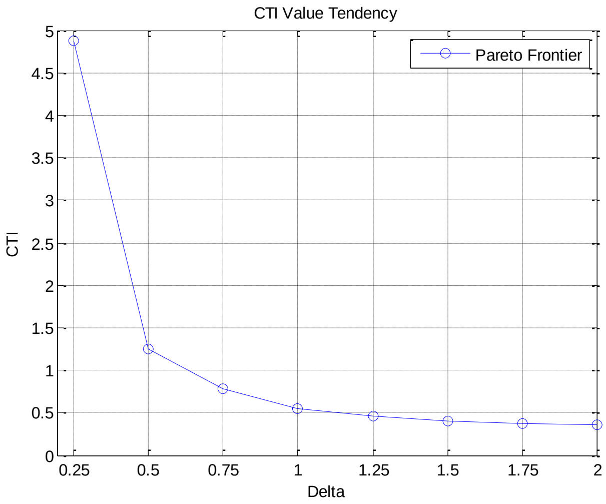

Figure 8 Pareto frontier of the weight parameter δ and the trend of the operating time CTI
Source: Own elaboration

It can be observed from Figure 8, that the minimum CTI operation time occurs when the weight parameter δ is located at the value 2. Which reveals that the best tuning for the weight parameter δ is 2.

Therefore, from Figures 6, 7 and 8 it can be observed that the best values for the weight parameters α, β and δ of the proposed fitness function is 2, 1, 2 when it obtains minimum results, since it is a DOCRs time minimization problem. Which were plotted from the data in Table 5, where it can be concluded that the weights 2, 1, 2 give better results and are shaded in golden color.

The plotted values from Table 5 for each weight parameter are in bold and color.

Next, the results of comparison of skill functions I, II, and III are presented in Table 6. The average values and standard deviation of DOCRs operation times in 50 independent simulations are analyzed.

		GA			
		tp(seg)	**tb(seg)**	**CTI(seg)**	**MC**
I	**Average**	0.34	0.90	0.56	16
	SD	0.01	0.03	0.03	--
II	**Average**	0.34	0.88	0.54	14
	SD	0.01	0.02	0.02	--
III	**Average**	0.46	1.13	0.67	0
	SD	0.02	0.07	0.05	--

Table 6 Average results and standard deviation of DOCRs operation times and coordination losses in 50 runs of independent simulations of skill functions I, II and III
Source: Own elaboration

It is observed from Table 6 that for the three skill functions, in spite of starting with random populations, all the simulations manage to converge, since they have a standard deviation (SD) of the operation times in the order of thousandths. In addition, it is observed that the times of primary operations, backup and CTI are in a very acceptable range of operation of protections. However, the key differentiating factor that highlights the superiority of the proposed fitness function (III) is that it has zero coordination loss. While the fitness functions I and II have 16 and 14 runs with coordination losses respectively. Which means that some line(s) are not adequately protected. And there may be cases of simultaneous firing or that the backup comes into function before the primary. From here the great advantage of the proposed suitability function (III) is revealed that all lines are protected by the protections adequately.

It is worth mentioning that the values of the three suitability functions were not compared because as they are different suitability functions they result in a different value. Therefore, they cannot be compared.

In Table 7, the result of a simulation run with the proposed fitness function (III) is presented. It can be observed that the primary times, backups, CTI, are very practical. The primary and backup fault currents, protection coordination couples are also presented.

Primary	Backup	GA			Primary	Backup
		tp(s)	*tb(s)*	*CTI(s)*	Icc(A)	Icc(A)
4 6	*1 4*	*0.44*	*1.15*	*0.71*	*7493*	*2338*
1 5	*4 1*	*0.64*	*2.23*	*1.60*	*7676*	*1900*
1 6	*4 1*	*0.37*	*2.19*	*1.81*	*8572*	*1921*
5 6	*1 5*	*0.43*	*0.75*	*0.31*	*6554*	*3676*
1 4	*5 1*	*0.33*	*0.77*	*0.43*	*7955*	*2363*
1 6	*5 1*	*0.37*	*0.73*	*0.36*	*8572*	*2508*
6 4	*1 6*	*0.48*	*0.93*	*0.45*	*4370*	*2127*
6 5	*1 6*	*0.48*	*0.88*	*0.40*	*5366*	*2231*
1 4	*6 1*	*0.33*	*1.33*	*1.00*	*7955*	*1451*
1 5	*6 1*	*0.64*	*1.09*	*0.45*	*7676*	*1633*
6 1	*4 6*	*0.32*	*0.89*	*0.56*	*5620*	*3186*
6 5	*4 6*	*0.48*	*0.92*	*0.44*	*5366*	*3104*
4 1	*6 4*	*0.44*	*0.97*	*0.53*	*7590*	*2433*
6 1	*5 6*	*0.32*	*0.87*	*0.55*	*5620*	*2405*
6 4	*5 6*	*0.48*	*0.96*	*0.48*	*4370*	*2216*
5 1	*6 5*	*0.54*	*0.86*	*0.32*	*5291*	*2413*
AVERAGE		**0.44**	**1.09**	**0.65**	--	--

Table 7 Primary, backup, CTI and fault currents of the coordination pairs of a simulation run
Source: Own elaboration

It can be emphasized that the CTI times meet the constraint presented in equation 2, this reveals that all protection couples are coordinated and there is no coordination loss. The average primary, backup and CTI times of the 6-bus meshed system in a simulation run are: 0.44, 1.09, 0.65 seconds respectively.

The optimized DOCRs settings of the same simulation run are presented in Table 8. Using the proposed fitness function (III) it can be observed that it channels the algorithm towards minimizing the times of primary operations, backups and CTI using small dial parameters and overload factor for the starting current. Thus, this allows the protections to operate faster in the event of electrical faults in the lines.

DOCR	GA	
	dial	*Ip*
1 4	0.53	654
4 1	0.67	675
1 5	1.23	286
5 1	0.99	283
1 6	0.69	436
6 1	0.52	448
4 6	0.70	621
6 4	0.56	595
5 6	0.75	437
6 5	0.78	418

Table 8 Dial and inrush current settings for the overcurrent relays of a simulation run
Source: Own elaboration

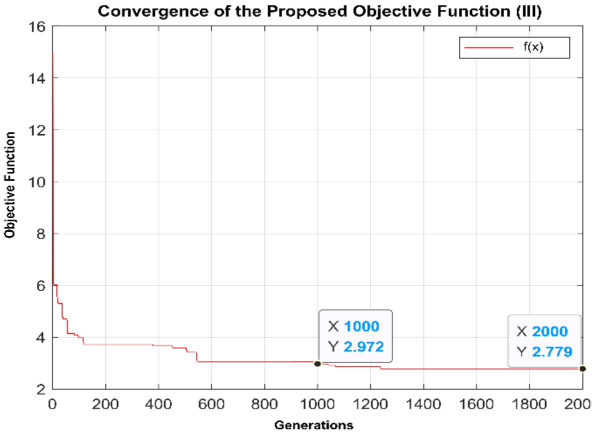

Figure 9 Convergence of the GA for the 6-bus system meshed from a simulation run
Source: Own elaboration

Figure 9 presents the GA convergence trend using the proposed fitness function (III) for the optimization of protections in a simulation run. It is observed that the fitness function is decreasing, which reveals that the proposed fitness function is guiding the algorithm towards the search for minimum results of operation times.

On the other hand, it can be detected that there are only slight improvements to the results after 1,000 generations. It has as 2,972 in the 1,000th generation and 2,799 in the 2,000th generation. In other words, it reveals that the coordination problem has been solved since at 1,000 generations it has almost converged to the proposed fitness function (III). Therefore, the running time of the algorithm for optimization could have been halved if desired by the user by setting the convergence criterion as 1,000 generations. It is worth mentioning that the GA algorithm with the proposed fitness function (III) requires approximately and only 130 seconds to run and evaluate the two thousand generations for the coordination of DOCRs.

Acknowledgement

The authors are grateful for the support and effort of the Universidad Autónoma de Campeche for its researchers to disseminate the research topics in which they are immersed.

Conclusions

The coordination of protections manually is a very complex work that can take a long time. However, caution should be exercised when opting for the support of optimization algorithms to solve this problem.

As shown in the study results in this article, the algorithms converge to different results (settings) when different skill functions are used. Some of them lead to the loss of coordination of protections, leaving some line(s) without protection in case of power failure scenarios.

Therefore, a proper suitability function proposal for this problem is of utmost importance. In addition, proper tuning of the weights of the fitness function is crucial. Since, without proper weights, the algorithm may get lost in the multiple local minima and giving results as coordination losses as well.

It is concluded from the studies conducted that the objective has been met and the hypothesis is affirmative. The proposed fitness function (III) is adequate and the study of tuning weights are appropriate for electrical networks with diverse connectivity and complexity.

References

Alam M.N., Das B. and Pant V. (November 2015). A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination, *Electric Power Systems Research*, 128, 39-52.

Amraee T. (July 2012). Coordination of Directional Overcurrent Relays Using Seeker Algorithm. *IEEE Transactions on Power Delivery,* 27 (3), 1415-1422.

Bedekar P. & Bhide S. (January 2011). Optimum coordination of directional overcurrent relays using the hybrid GA-NLP approach. *IEEE Transactions on Power Delivery*, 26 (1), 109-119.

Bedekar P. & Bhide S. (September 2011). Optimum coordination of overcurrent relay timing using continuous genetic algorithm. *Elsevier Expert Systems with Applications*, 38 (9), 11286-11292.

Blackburn J. L. & Domin T. J. (2006). *Protective relaying, principles and applications*. (3rd edition). CRC Press Taylor & Francis Group.

Gers J. M. & Holmes E. J. (2011). *Protection of Electricity Distribution Networks*. (3rd edition). IET.

IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays, IEEE std C37.112-1996.

Kalage A.A. and Ghawghawe N.D.. (March 2016). Optimum coordination of directional overcurrent relays using modified adaptive teaching learning based optimization algorithm, *Springer Intelligent Industrial Systems*., 2 (1), 55-71.

Mansour M.M., Mekhamer S.F., and El-Kharbawe N.E-S.. (July 2007). A modified particle swarm optimizer for the coordination of directional overcurrent relays, *IEEE Transactions on Power Delivery*, 22 (3), 1400-1410.

Othman A.M. and Abdelaziz A.Y.. (2016). Enhanced Backtracking Search Algorithm for Optimal Coordination of Directional Over-current Relays Including Distributed Generation, *Electric Power Components and Systems*, 44 (3), 278-290.

Saadat H. (1999). *Power system analysis*. McGraw-Hill.

Saha D., Datta A., Saha B.K. and Das P.. (March 2016). A comparative study on the computation of directional overcurrent relay coordination in power systems using PSO and TLBO based optimization, *Engineering Computations*., 33 (2), 603-621.

Srivastava A., Tripathi J.M., Mohanty S.R. and Panda B.. (2016). Optimal Over-current Relay Coordination with Distributed Generation Using Hybrid Particle Swarm Optimization–Gravitational Search Algorithm, *Electric Power Components and Systems*, 44 (5), 506-517.

Zeineldin H., El-Saadany E. & Salama M. (July 2006). Optimal coordination of overcurrent relays using a modified particle swarm optimization. *Electric Power Systems Research*, 76 (11), 988-995.