OMEGA GREY WOLF OPTIMIZER (ωGWO) FOR OPTIMIZATION OF OVERCURRENT RELAYS COORDINATION WITH DISTRIBUTED GENERATION

NOOR ZAIHAH BINTI JAMAL

DOCTOR OF PHILOSOPHY

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

_____

(Supervisor's Signature)

Full Name : DR. MOHD HERWAN BIN SULAIMAN

Position : ASSOCIATE PROFESSOR

Date :

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

_____

(Student's Signature)

Full Name : NOOR ZAIHAH BINTI JAMAL

ID Number : PEE15003

Date :

OMEGA GREY WOLF OPTIMIZER (ωGWO) FOR OPTIMIZATION OF OVERCURRENT RELAYS COORDINATION WITH DISTRIBUTED GENERATION

NOOR ZAIHAH BINTI JAMAL

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Doctor of Philosophy

Faculty of Electrical & Electronics Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2019

ACKNOWLEDGEMENTS

Alhamdulillah, praises belongs to Allah S.W.T for pouring me with His blessing and strength throughout my path of doing the research.

First and foremost, thanks to my supervisor, Assoc. Prof. Dr. Mohd Herwan bin Sulaiman for his supervision, support, encouraging words and positive vibes throughout my journey. May Allah bless his effort and endowed him with Mercy and *Rahmah*. I would like to express my sincere thanks to Mr. Omar bin Aliman for his valuable ideas at the very beginning of my PhD journey and also for the helpful assistance during the journal preparations and proofreading. My gratitude also goes to Dr. Zuriani binti Mustaffa for proofreading my journals. I would also acknowledge the financial support received from Universiti Malaysia Pahang for the fee discounts during my study.

My warmest and hearties appreciation to my beloved parents, Ramelah binti Rafie & Jamal bin Awang for their inspirational love, Du'a and encouragement for me to pursue study in PhD. My hearties thanks and love also goes to my supportive husband, Mohd Zainul Ariffin bin Mohd Alias for his unlimited reassurance during my ups and down. Special appreciation to my children, Muhammad Rayyan Iman & Noor Raudhah Amani for their understanding and consideration during constraints' situation, as well as to my siblings, for their encouragement and financial aids when I faced problems with the scholarship matter. Last but not least, whole family members and friends whom did encouraged me directly or indirectly.

ABSTRAK

Pengganti lebihan arus jenis berlawanan masa minima tetap (IDMT) adalah peranti pelindung yang utama yang dipasang dalam rangkaian pembekalan pengagihan elektrik. Peranti tersebut digunakan untuk mengesan dan mengasingkan bahagian yang bermasalah daripada sistem utama untuk memastikan bekalan elektrik dapat dibekalkan seperti biasa semasa keadaan darurat. Koordinasi pelindung secara keseluruhan adalah sangat rumit dan ianya tidak dapat dilakukan oleh cara lazim. Tesis ini mencadangkan algoritma meta-heuristik yang dinamakan "Grey Wolf Optimizer (GWO)" untuk meminimakan masa operasi bagi pengganti lebihan arus dan memenuhi kehendak had-had yang ditetapkan. GWO diinspirasikan oleh kelakuan memburu oleh serigala kelabu yang mempunyai hirarki sosial yang dominan. Algoritma sedia ada yang terkenal yang dikenali sebagai "particle swarm optimizer (PSO)", "differential evolution (DE)" dan "Biogeography-based Optimizer (BBO)" juga digunakan untuk membuktikan kecemerlangan GWO dengan menggunakan pengaturcaraan simulasi MATLAB dilengkapi dengan sempadan dan had yang sama bagi tujuan perbandingan yang adil. Kajian diteruskan dengan penambahbaikan pada formula penerokaan oleh algoritma GWO yang asal untuk meningkatkan kebolehan memburu dikenali sebagai Omega GWO (ωGWO). Algorithm ωGWO diuji pada rangkaian sistem pengagihan sebenar dengan diintegrasi oleh penjana yang diedarkan (DG). Pengujian ini adalah untuk menyiasat kesan impak negatif oleh integrasi DG kepada konfigurasi asal pengganti lebihan arus. Algoritma GWO telah diuji ke atas empat kes yang berbeza iaitu *IEEE 3 bus, IEEE 8 bus, 9 bus* dan *IEEE 15 bus* dengan keluk songsang normal (NI) untuk kesemua kes dan keluk sangat songsang (VI) untuk kes terpilih. Rangkaian sistem 7 bas pengagihan sebenar di Malaysia telah dipilih untuk menyiasat dan mencadangkan lokasi integrasi DG yang paling optima yang mana mempunyai kurang impak negatif kepada konfigurasi asal. Hasil simulasi telah menunjukkan bahawa algoritma GWO mampu menghasilkan penyelesaian yang lebih baik dengan masa operasi bagi pengganti lebihan arus yang lebih rendah berbanding algoritma yang lain. Masa operasi pengganti lebihan arus oleh algoritma GWO telah dikurangkan sebanyak 0.09 saat dan 0.46 saat berbanding dengan algoritma PSO dan DE. Dalam pada masa yang sama, masa penumpuan oleh algoritma GWO juga telah dikurang sebanyak 23 saat dan 0.46 saat masing–masing berbanding algoritma DE dan PSO. Keteguhan algoritma GWO telah dibuktikan dengan keputusan sisihan piawai yang rendah dengan 1.7142 saat berbanding algorithma Biogeography-based Optimizer (BBO). Cadangan penambahbaikan kepada algoritma GWO yang asal iaitu ωGWO telah menunjukkan penurunan sebanyak 55% dan 19% masing-masing berbanding algoritma GA-NLP dan PSO-LP. Perbandingan dengan algoritma asal GWO jugak telah menunjukkan penurunan masa operasi sebanyak 0.7%. Susulan dari keputusan yang diperolehi dalam kajian ini telah mendapati bahawa ωGWO adalah algoritma yang memenuhi sisihan piawai dan sesuai untuk diaplikasikan kepada rangkaian sistem pengagihan elektrik di masa hadapan yang lebih kompleks.

ABSTRACT

Inverse definite minimum time (IDMT) overcurrent relays (OCRs) are among protective devices installed in electrical power distribution networks. The devices are used to detect and isolate the faulty area from the system in order to maintain the reliability and availability of the electrical supply during contingency condition. The overall protection coordination is thus very complicated and could not be satisfied using the conventional method moreover for the modern distribution system. This thesis apply a meta-heuristic algorithm called Grey Wolf Optimizer (GWO) to minimize the overcurrent relays operating time while fulfilling the inequality constraints. GWO is inspired by the hunting behavior of the grey wolf which have firm social dominant hierarchy. Comparative studies have been performed in between GWO and the other well-known methods such as Differential Evolution (DE), Particle Swarm Optimizer (PSO) and Biogeography-based Optimizer (BBO), to demonstrate the efficiency of the GWO. The study is resumed with an improvement to the original GWO's exploration formula named as Omega-GWO (ωGWO) to enhance the hunting ability. The ωGWO is then implemented to the real-distribution network with the distributed generation (DG) in order to investigate the drawbacks of the DG insertion towards the original overcurrent relays configuration setting. The GWO algorithm is tested to four different test cases which are IEEE 3 bus (consists of six OCRs), IEEE 8 bus (consists of 14 OCRs), 9 bus (consists of 24 OCRs) and IEEE 15 bus (consists of 42 OCRs) test systems with normal inverse (NI) characteristic curve for all test cases and very inverse (VI) curve for selected cases to test the flexibility of the GWO algorithm. The real-distribution network in Malaysia which originally without DG is chosen, to investigate and recommend the optimal DG placement that have least negative impact towards the original overcurrent coordination setting. The simulation results from this study has established that GWO is able to produce promising solutions by generating the lowest operating time among other reviewed algorithms. The superiority of the GWO algorithm is proven with relays' operational time are reduced for about 0.09 seconds and 0.46 seconds as compared to DE and PSO respectively. In addition, the computational time of the GWO algorithm is faster than DE and PSO with the respective reduced time is 23 seconds and 37 seconds. In Moreover, the robustness of GWO algorithm is establish with low standard deviation of 1.7142 seconds as compared to BBO. The ωGWO has shown an improvement for about 55% and 19% compared to other improved and hybrid method of GA-NLP and PSO-LP respectively and 0.7% reduction in relays operating time compared to the original GWO. The investigation to the DG integration has disclosed that the scheme is robust and appropriate to be implemented for future system operational and topology revolutions.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

T_i	Relay operating time
$I_{Ri,l}$	Fault current at location, *l*
a_i	Weight factor
R_i	Relay at *ith*
TMSi	Time multiplier setting at *ith*
PSi	Plug setting at *ith*
I_n	Normal current rating
$I_{f\,min}$	Minimum value of current
Ti_{bc}	Operating time for back-up relay
Ti_{pr}	Operating time for primary relay
α	Alpha wolf
β	Beta wolf
δ	Delta wolf
ω	Omega wolf

LIST OF ABBREVIATIONS

ALO	Ant lion optimizer
BBO	Biogeography-based Optimization
CGA	Continuous Genetic Algorithm
CSA	Cuckoo Search Algorithm
CTI	Coordination time interval
DE	Differential Evolution
DG	Distributed generation
EFO	Electromagnetic Field Optimization
FA	Firefly algorithm
GA	Genetic Algorithm
GWO	Grey wolf optimizer
HEA	Hybrid Evolutionary Algorithm
HGA-NLP	Hybrid GA-NLP
HGAPSOA	Hybrid GA and PSO Algorithm
HGSA	Hybrid Gravitational Search Algorithm
HSA	Harmony Search Algorithm
IGSO	Improved Group Search Optimization
ωGWO	Omega grey wolf optimizer
MDE	Modified Differential Evolution
MFO	Moth flame optimizer
MPSO	Modified Particle Swarm Optimization
NFL	The No Free Lunch
NI	Normal inverse characteristic curve
OF	Objective function
PS	Plug setting
PSO	Particle Swarm Optimization
PSO-LP	Particle Swarm Optimization-Linear Programming
PU	Pick-up setting
SA	Seeker Algorithm
TDS	Time dial setting
TLBO	Teaching Learning-base Optimization
TMS	Time multiplier setting
VI	Very inverse characteristic curve

REFERENCES

Abdelaziz, A. Y., Talaat, H. E. A., Nosseir, A. I., & Hajjar, A. A. (2002). An adaptive protection scheme for optimal coordination of overcurrent relays. *Electric Power Systems Research, 61*(1), 1-9. doi:http://dx.doi.org/10.1016/S0378-7796(01)00176-6

Abyane, H. A., Faez, K., & Karegar, H. K. (1997, 4-4 Dec. 1997). *A new method for overcurrent relay (O/C) using neural network and fuzzy logic.* Paper presented at the TENCON '97. IEEE Region 10 Annual Conference. Speech and Image Technologies for Computing and Telecommunications., Proceedings of IEEE.

Ackermann, T., & Knyazkin, V. (2002, 6-10 Oct. 2002). *Interaction between distributed generation and the distribution network: operation aspects.* Paper presented at the IEEE/PES Transmission and Distribution Conference and Exhibition.

Al-Roomi, A. R., & El-Hawary, M. E. (2017, April 30 2017-May 3 2017). *Optimal coordination of directional overcurrent relays using hybrid BBO-LP algorithm with the best extracted time-current characteristic curve.* Paper presented at the 2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE).

Alam, M. N., Das, B., & Pant, V. (2015). A comparative study of metaheuristic optimization approaches for directional overcurrent relays coordination. *Electric Power Systems Research, 128*, 39-52. doi:http://dx.doi.org/10.1016/j.epsr.2015.06.018

Albasri, F. A., Alroomi, A. R., & Talaq, J. H. (2015). Optimal Coordination of Directional Overcurrent Relays Using Biogeography-Based Optimization Algorithms. *IEEE Transactions on Power Delivery, 30*(4), 1810-1820. doi:10.1109/TPWRD.2015.2406114

Ali, A., Buderi, F. A., Hanafiah, M. A. M., & Baharudin, Z. A. (2016, 28-29 Nov. 2016). *Assessment on the impact of distributed generation to the distribution network overcurrent protection in Malaysia.* Paper presented at the 2016 IEEE International Conference on Power and Energy (PECon).

Ali, E. S., Abd Elazim, S. M., & Abdelaziz, A. Y. (2017). Ant Lion Optimization Algorithm for optimal location and sizing of renewable distributed generations. *Renewable Energy, 101*, 1311-1324. doi:https://doi.org/10.1016/j.renene.2016.09.023

Alipour, M., Teimourzadeh, S., & Seyedi, H. (2015). Improved group search optimization algorithm for coordination of directional overcurrent relays. *Swarm and Evolutionary Computation, 23*, 40-49. doi:http://dx.doi.org/10.1016/j.swevo.2015.03.003

Alkaran, D. S., Vatani, M. R., Sanjari, M. J., Gharehpetian, G. B., & Naderi, M. S. (2016). Optimal Overcurrent Relay Coordination in Interconnected Networks by Using Fuzzy-Based GA Method. *IEEE Transactions on Smart Grid, PP*(99), 1-1. doi:10.1109/TSG.2016.2626393

Amraee, T. (2012). Coordination of Directional Overcurrent Relays Using Seeker Algorithm. *IEEE Transactions on Power Delivery, 27*(3), 1415-1422. doi:10.1109/TPWRD.2012.2190107

Bansal, J. C., & Deep, K. (2008, 21-23 Sept. 2008). *Optimization of directional overcurrent relay times by particle swarm optimization*. Paper presented at the Swarm Intelligence Symposium, 2008. SIS 2008. IEEE.

Barzegari, M., Bathaee, S. M. T., & Alizadeh, M. (2010, 16-19 May 2010). *Optimal coordination of directional overcurrent relays using harmony search algorithm.* Paper presented at the 2010 9th International Conference on Environment and Electrical Engineering.

Bastiao, F., Cruz, P., & Fiteiro, R. (2008, 28-30 May 2008). *Impact of distributed generation on distribution networks.* Paper presented at the 2008 5th International Conference on the European Electricity Market.

Bedekar, P. P., & Bhide, S. R. (2011). Optimum Coordination of Directional Overcurrent Relays Using the Hybrid GA-NLP Approach. *IEEE Transactions on Power Delivery, 26*(1), 109-119. doi:10.1109/TPWRD.2010.2080289

Bedekar, P. P., & Bhide, S. R. (2011). Optimum coordination of overcurrent relay timing using continuous genetic algorithm. *Expert Systems with Applications, 38*(9), 11286-11292. doi:http://dx.doi.org/10.1016/j.eswa.2011.02.177

Birla, D., Maheshwari, R. P., & Gupta, H. O. (2006). A new nonlinear directional overcurrent relay coordination technique, and banes and boons of near-end faults based approach. *Power Delivery, IEEE Transactions on, 21*(3), 1176-1182. doi:10.1109/TPWRD.2005.861325

Birla, D., Maheshwari Rudra, P., & Gupta Hari, O. (2005). Time-Overcurrent Relay Coordination: A Review *International Journal of Emerging Electric Power Systems* (Vol. 2).

Blum, C., Puchinger, J., Raidl, G. R., & Roli, A. (2011). Hybrid metaheuristics in combinatorial optimization: A survey. *Applied Soft Computing, 11*(6), 4135-4151. doi:https://doi.org/10.1016/j.asoc.2011.02.032

Bouchekara, H. R. E. H., Zellagui, M., & Ma.Abido. Optimal Coordination of Directional Overcurrent Relays Using a Modified Electromagnetic Field Optimization Algorithm. *Applied Soft Computing*. doi:http://dx.doi.org/10.1016/j.asoc.2017.01.037

Boussaïd, I., Lepagnot, J., & Siarry, P. (2013). A survey on optimization metaheuristics. *Information Sciences, 237*, 82-117. doi:https://doi.org/10.1016/j.ins.2013.02.041

Boutsika, T. N., & Papathanassiou, S. A. (2008). Short-circuit calculations in networks with distributed generation. *Electric Power Systems Research, 78*(7), 1181-1191. doi:https://doi.org/10.1016/j.epsr.2007.10.003

Britto, T. M. d., Morais, D. R., Marin, M. A., Rolim, J. G., Zurn, H. H., & Buendgens, R. F. (2004, 8-11 Nov. 2004). *Distributed generation impacts on the coordination of*

protection systems in distribution networks. Paper presented at the 2004 IEEE/PES Transmision and Distribution Conference and Exposition: Latin America (IEEE Cat. No. 04EX956).

Chaitusaney, S., & Yokoyama, A. (2005, Nov. 29 2005-Dec. 2 2005). *Impact of protection coordination on sizes of several distributed generation sources.* Paper presented at the 2005 International Power Engineering Conference.

Chaitusaney, S., & Yokoyama, A. (2008). Prevention of Reliability Degradation from Recloser–Fuse Miscoordination Due To Distributed Generation. *IEEE Transactions on Power Delivery, 23*(4), 2545-2554. doi:10.1109/TPWRD.2007.915899

Chawla, A., Bhalja, B. R., Panigrahi, B. K., & Singh, M. (2018). Gravitational Search Based Algorithm for Optimal Coordination of Directional Overcurrent Relays Using User Defined Characteristic. *Electric Power Components and Systems, 46*(1), 43-55. doi:10.1080/15325008.2018.1431982

Chelliah, T. R., Thangaraj, R., Allamsetty, S., & Pant, M. (2014a). Coordination of directional overcurrent relays using opposition based chaotic differential evolution algorithm. *International Journal of Electrical Power & Energy Systems, 55*, 341-350. doi:http://dx.doi.org/10.1016/j.ijepes.2013.09.032

Chelliah, T. R., Thangaraj, R., Allamsetty, S., & Pant, M. (2014b). Coordination of directional overcurrent relays using opposition based chaotic differential evolution algorithm. *International Journal of Electrical Power & Energy Systems, 55*(0), 341-350. doi:http://dx.doi.org/10.1016/j.ijepes.2013.09.032

Chen, J., Fan, R., Duan, X., & Cao, J. (2009, 6-7 April 2009). *Penetration level optimization for DG considering reliable action of relay protection device constrains.* Paper presented at the 2009 International Conference on Sustainable Power Generation and Supply.

Chen, Y., Wang, Z., & Liu, X. (2010, 18-20 June 2010). *Automated point feature label placement using backtracking algorithm with an adjacent graph.* Paper presented at the 2010 18th International Conference on Geoinformatics.

Cheng-Hung, L., & Chao-Rong, C. (2007, 5-8 Nov. 2007). *Using Genetic Algorithm for Overcurrent Relay Coordination in Industrial Power System.* Paper presented at the Intelligent Systems Applications to Power Systems, 2007. ISAP 2007. International Conference on.

Chunlin, X., Xiufen, Z., Rongxiang, Y., & Chuansheng, W. (2008, 1-6 June 2008). *Optimal coordination of protection relays using new hybrid evolutionary algorithm.* Paper presented at the Evolutionary Computation, 2008. CEC 2008. (IEEE World Congress on Computational Intelligence). IEEE Congress on.

Coelho, L. d. S., & Mariani, V. C. (2012). Firefly algorithm approach based on chaotic Tinkerbell map applied to multivariable PID controller tuning. *Computers & Mathematics with Applications, 64*(8), 2371-2382. doi:https://doi.org/10.1016/j.camwa.2012.05.007

Conti, S. (2009). Analysis of distribution network protection issues in presence of dispersed generation. *Electric Power Systems Research, 79*(1), 49-56. doi:https://doi.org/10.1016/j.epsr.2008.05.002

Conti, S., & Nicotra, S. (2009). Procedures for fault location and isolation to solve protection selectivity problems in MV distribution networks with dispersed generation. *Electric Power Systems Research, 79*(1), 57-64. doi:https://doi.org/10.1016/j.epsr.2008.05.003

Dai, C., Chen, W., Zhu, Y., & Zhang, X. (2009). Seeker Optimization Algorithm for Optimal Reactive Power Dispatch. *IEEE Transactions on Power Systems, 24*(3), 1218-1231. doi:10.1109/TPWRS.2009.2021226

Dai, C., Zhu, Y., & Chen, W. (2007). *Seeker Optimization Algorithm,* Berlin, Heidelberg.

Damborg, M. J., Ramaswami, R., Venkata, S. S., & Postforoosh, J. M. (1984). Computer Aided Transmission Protection System Design Part I: Alcorithms. *IEEE Transactions on Power Apparatus and Systems, PAS-103*(1), 51-59. doi:10.1109/TPAS.1984.318576

Damchi, Y., Mashhadi, H. R., Sadeh, J., & Bashir, M. (2011, 16-20 Oct. 2011). *Optimal coordination of directional overcurrent relays in a microgrid system using a hybrid particle swarm optimization.* Paper presented at the Advanced Power System Automation and Protection (APAP), 2011 International Conference on.

Darji, G. U., Patel, M. J., Rajput, V. N., & Pandya, K. S. (2015, 12-14 Aug. 2015). *A tuned cuckoo search algorithm for optimal coordination of Directional Overcurrent Relays.* Paper presented at the Power and Advanced Control Engineering (ICPACE), 2015 International Conference on.

Das, S., & Suganthan, P. N. (2011). Differential Evolution: A Survey of the State-of-the-Art. *IEEE Transactions on Evolutionary Computation, 15*(1), 4-31. doi:10.1109/TEVC.2010.2059031

Eissa, M. M. (2015). Protection techniques with renewable resources and smart grids—A survey. *Renewable and Sustainable Energy Reviews, 52*, 1645-1667. doi:https://doi.org/10.1016/j.rser.2015.08.031

El-khattam, W., & Sidhu, T. S. (2009). Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study. *IET Renewable Power Generation, 3*(4), 415-425. doi:10.1049/iet-rpg.2008.0015

Fister, I., Fister, I., Yang, X.-S., & Brest, J. (2013). A comprehensive review of firefly algorithms. *Swarm and Evolutionary Computation, 13*, 34-46. doi:https://doi.org/10.1016/j.swevo.2013.06.001

Funmilayo, H. B., & Butler-Purry, K. L. (2009, 15-18 March 2009). *An approach to mitigate the impact of distributed generation on the Overcurrent Protection scheme for radial feeders.* Paper presented at the 2009 IEEE/PES Power Systems Conference and Exposition.

Gandomi, A. H., Yang, X.-S., & Alavi, A. H. (2013). Cuckoo search algorithm: a metaheuristic approach to solve structural optimization problems. *Engineering with Computers, 29*(1), 17-35. doi:10.1007/s00366-011-0241-y

Gandomi, A. H., Yang, X. S., Talatahari, S., & Alavi, A. H. (2013). Firefly algorithm with chaos. *Communications in Nonlinear Science and Numerical Simulation, 18*(1), 89-98. doi:https://doi.org/10.1016/j.cnsns.2012.06.009

Geem, Z. W., Kim, J. H., & Loganathan, G. V. (2001). A New Heuristic Optimization Algorithm: Harmony Search. *SIMULATION, 76*(2), 60-68. doi:10.1177/003754970107600201

Gerhart, S. L., & Yelowitz, L. (1976). Control Structure Abstractions of the Backtracking Programming Technique. *IEEE Transactions on Software Engineering, SE-2*(4), 285-292. doi:10.1109/TSE.1976.233834

Ghosh, S., Ghoshal, S. P., & Ghosh, S. (2010). Optimal sizing and placement of distributed generation in a network system. *International Journal of Electrical Power & Energy Systems, 32*(8), 849-856. doi:https://doi.org/10.1016/j.ijepes.2010.01.029

Girgis, A., & Brahma, S. (2001, 2001). *Effect of distributed generation on protective device coordination in distribution system.* Paper presented at the LESCOPE 01. 2001 Large Engineering Systems Conference on Power Engineering. Conference Proceedings. Theme: Powering Beyond 2001 (Cat. No.01ex490).

Gogna, A., & Tayal, A. (2013). Metaheuristics: review and application. *Journal of Experimental & Theoretical Artificial Intelligence, 25*(4), 503-526. doi:10.1080/0952813X.2013.782347

Gokhale, S. S., & Kale, V. S. (2016). An application of a tent map initiated Chaotic Firefly algorithm for optimal overcurrent relay coordination. *International Journal of Electrical Power & Energy Systems, 78*, 336-342. doi:http://dx.doi.org/10.1016/j.ijepes.2015.11.087

Goldberg, D. E. (2006). *Genetic algorithms*: Pearson Education India.

Haupt, R. L., & Haupt, S. E. . (2004). *Practical genetic algorithms* (2nd ed.). New Jersey: John Wiley and Sons, Inc.

Heidari, A. A., & Pahlavani, P. (2017). An efficient modified grey wolf optimizer with Lévy flight for optimization tasks. *Applied Soft Computing, 60*, 115-134. doi:https://doi.org/10.1016/j.asoc.2017.06.044

Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems*: The University of Michigan Press, Ann Arbor, M.

Hussain, M. H., Musirin, I., Abidin, A. F., & Rahim, S. R. A. (2014, 24-25 March 2014). *Directional overcurrent relay coordination problem using Modified Swarm Firefly Algorithm considering the effect of population size.* Paper presented at the Power Engineering and Optimization Conference (PEOCO), 2014 IEEE 8th International.

Hussain, M. H., Rahim, S. R. A., & Musirin, I. (2013). Optimal Overcurrent Relay Coordination: A Review. *Procedia Engineering, 53*(0), 332-336. doi:http://dx.doi.org/10.1016/j.proeng.2013.02.043

J.Holmes, J. M. G. a. E. (2011). *Protection of Electricity Distribution Networks* (3rd edition ed.): The Institution of Engineering and Technology, London, United Kingdom.

Jangir, N., Pandya, M. H., Trivedi, I. N., Bhesdadiya, R. H., Jangir, P., & Kumar, A. (2016, 5-6 March 2016). *Moth-Flame optimization Algorithm for solving real challenging constrained engineering optimization problems.* Paper presented at the 2016 IEEE Students' Conference on Electrical, Electronics and Computer Science (SCEECS).

Kamel, A., Alaam, M. A., Azmy, A. M., & Abdelaziz, A. Y. (2013). Protection Coordination for Distribution Systems in Presence of Distributed Generators. *Electric Power Components and Systems, 41*(15), 1555-1566. doi:10.1080/15325008.2013.835361

Kar, A. K. (2016). Bio inspired computing – A review of algorithms and scope of applications. *Expert Systems with Applications, 59*(Supplement C), 20-32. doi:https://doi.org/10.1016/j.eswa.2016.04.018

Kauhaniemi, K., & Kumpulainen, L. (2004, 5-8 April 2004). *Impact of distributed generation on the protection of distribution networks.* Paper presented at the 2004 Eighth IEE International Conference on Developments in Power System Protection.

Kuang, H., Li, S., & Wu, Z. (2011, 16-18 Sept. 2011). *Discussion on advantages and disadvantages of distributed generation connected to the grid.* Paper presented at the 2011 International Conference on Electrical and Control Engineering.

Lestari, D. S., Pujiantara, M., Purnomo, M. H., & Rahmatullah, D. (2018, 6-7 March 2018). *Adaptive DOCR coordination in loop distribution system with distributed generation using firefly algorithm-artificial neural network.* Paper presented at the 2018 International Conference on Information and Communications Technology (ICOIACT).

Li, M., Du, W., & Nian, F. (2014). An Adaptive Particle Swarm Optimization Algorithm Based on Directed Weighted Complex Network. *Mathematical Problems in Engineering, 2014*, 7. doi:10.1155/2014/434972

Mancer, N., Mahdad, B., Srairi, K., Hamed, M., & Hadji, B. (2015). Optimal Coordination of Directional Overcurrent Relays Using PSO-TVAC. *Energy Procedia, 74*, 1239-1247. doi:http://dx.doi.org/10.1016/j.egypro.2015.07.768

Manditereza, P. T., & Bansal, R. (2016). Renewable distributed generation: The hidden challenges – A review from the protection perspective. *Renewable and Sustainable Energy Reviews, 58*, 1457-1465. doi:https://doi.org/10.1016/j.rser.2015.12.276

Mansour, M. M., Mekhamer, S. F., & El-Kharbawe, N. (2007). A Modified Particle Swarm Optimizer for the Coordination of Directional Overcurrent Relays. *IEEE Transactions on Power Delivery, 22*(3), 1400-1410. doi:10.1109/TPWRD.2007.899259

Medjahed, S. A., Ait Saadi, T., Benyettou, A., & Ouali, M. (2016). Gray Wolf Optimizer for hyperspectral band selection. *Applied Soft Computing, 40*, 178-186. doi:http://dx.doi.org/10.1016/j.asoc.2015.09.045

Mirjalili, S. (2015a). The Ant Lion Optimizer. *Advances in Engineering Software, 83*, 80-98. doi:https://doi.org/10.1016/j.advengsoft.2015.01.010

Mirjalili, S. (2015b). Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm. *Knowledge-Based Systems, 89*, 228-249. doi:https://doi.org/10.1016/j.knosys.2015.07.006

Mirjalili, S., Mirjalili, S., & Hatamlou, A. (2015). *Multi-Verse Optimizer: a nature-inspired algorithm for global optimization* (Vol. 27).

Mirjalili, S., Mirjalili, S. M., & Lewis, A. (2014). Grey Wolf Optimizer. *Advances in Engineering Software, 69*, 46-61. doi:http://dx.doi.org/10.1016/j.advengsoft.2013.12.007

Mittal, N., Singh, U., & Sohi, B. S. (2016). Modified Grey Wolf Optimizer for Global Engineering Optimization. *Applied Computational Intelligence and Soft Computing, 2016*, 16. doi:10.1155/2016/7950348

Mohanty, B. (2018). Performance analysis of moth flame optimization algorithm for AGC system. *International Journal of Modelling and Simulation*, 1-15. doi:10.1080/02286203.2018.1476799

Moravej, Z., Jazaeri, M., & Gholamzadeh, M. (2012). Optimal coordination of distance and over-current relays in series compensated systems based on MAPSO. *Energy Conversion and Management, 56*, 140-151.

Mousavi Motlagh, S. H., & Mazlumi, K. (2014). Optimal Overcurrent Relay Coordination Using Optimized Objective Function. *ISRN Power Engineering, 2014*, 10. doi:10.1155/2014/869617

Muro, C., Escobedo, R., Spector, L., & Coppinger, R. P. (2011). Wolf-pack (Canis lupus) hunting strategies emerge from simple rules in computational simulations. *Behavioural Processes, 88*(3), 192-197. doi:https://doi.org/10.1016/j.beproc.2011.09.006

N.Jenkins. (2000). *Embedded Generation*: Institution of Engineering and Technology.

Nassif, A. (2018). An Analytical Assessment of Feeder Overcurrent Protection with Large Penetration of Distributed Energy Resources. *IEEE Transactions on Industry Applications*, 1-1. doi:10.1109/TIA.2018.2810260

Noghabi, A. S., Sadeh, J., & Mashhadi, H. R. (2009). Considering Different Network Topologies in Optimal Overcurrent Relay Coordination Using a Hybrid GA. *IEEE*

Transactions on Power Delivery, 24(4), 1857-1863. doi:10.1109/TPWRD.2009.2029057

P, D. P. R., V.C, V. R., & T, G. M. (2018). Ant Lion optimization algorithm for optimal sizing of renewable energy resources for loss reduction in distribution systems. *Journal of Electrical Systems and Information Technology, 5*(3), 663-680. doi:https://doi.org/10.1016/j.jesit.2017.06.001

Papaspiliotopoulos, V. A., Kurashvili, T. A., & Korres, G. N. (2014, 2-5 Nov. 2014). *Optimal coordination of directional overcurrent relays in distribution systems with distributed generation based on a hybrid PSO-LP algorithm.* Paper presented at the MedPower 2014.

Parmar, J. (2013). Type and Application of Overcurrent Relay. Retrieved from https://electrical-engineering-portal.com website:

Perez, L. G., & Urdaneta, A. J. (1999). Optimal coordination of directional overcurrent relays considering definite time backup relaying. *Power Delivery, IEEE Transactions on, 14*(4), 1276-1284. doi:10.1109/61.796218

Radosavljević, J., & Jevtić, M. (2016). Hybrid GSA-SQP algorithm for optimal coordination of directional overcurrent relays. *IET Generation, Transmission & Distribution, 10*(8), 1928-1937. doi:10.1049/iet-gtd.2015.1223

Rahmani, A., & MirHassani, S. A. (2014). A hybrid Firefly-Genetic Algorithm for the capacitated facility location problem. *283*, 70-78. doi:10.1016/j.ins.2014.06.002

Rajakumar, R., Amudhavel, J., Dhavachelvan, P., & Vengattaraman, T. (2017). GWO-LPWSN: Grey Wolf Optimization Algorithm for Node Localization Problem in Wireless Sensor Networks. *Journal of Computer Networks and Communications, 2017*, 10. doi:10.1155/2017/7348141

Rajput, V. N., & Pandya, K. S. (2017). Coordination of directional overcurrent relays in the interconnected power systems using effective tuning of harmony search algorithm. *Sustainable Computing: Informatics and Systems, 15*, 1-15. doi:https://doi.org/10.1016/j.suscom.2017.05.002

Rajput, V. N., Pandya, K. S., & Joshi, K. (2015, 24-27 June 2015). *Optimal coordination of Directional Overcurrent Relays using hybrid CSA-FFA method.* Paper presented at the Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2015 12th International Conference on.

Rao, R. V., Savsani, V. J., & Vakharia, D. P. (2011). Teaching–learning-based optimization: A novel method for constrained mechanical design optimization problems. *Computer-Aided Design, 43*(3), 303-315. doi:https://doi.org/10.1016/j.cad.2010.12.015

Rao, R. V., Savsani, V. J., & Vakharia, D. P. (2012). Teaching–Learning-Based Optimization: An optimization method for continuous non-linear large scale problems. *Information Sciences, 183*(1), 1-15. doi:https://doi.org/10.1016/j.ins.2011.08.006

Rashedi, E., Nezamabadi-pour, H., & Saryazdi, S. (2009). GSA: A Gravitational Search Algorithm. *Information Sciences, 179*(13), 2232-2248. doi:https://doi.org/10.1016/j.ins.2009.03.004

Razavi, F., Abyaneh, H. A., Al-Dabbagh, M., Mohammadi, R., & Torkaman, H. (2008). A new comprehensive genetic algorithm method for optimal overcurrent relays coordination. *Electric Power Systems Research, 78*(4), 713-720. doi:http://dx.doi.org/10.1016/j.epsr.2007.05.013

Reeves, C. (2003). *Genetic algorithms. In Handbook of Metaheuristics* (Vol. 57).

Sahoo, A., & Chandra, S. (2017). Multi-objective Grey Wolf Optimizer for improved cervix lesion classification. *Applied Soft Computing, 52*, 64-80. doi:http://dx.doi.org/10.1016/j.asoc.2016.12.022

Saleh, S. A., Ozkop, E., & Aljankawey, A. S. (2016). The Development of a Coordinated Anti-Islanding Protection for Collector Systems With Multiple Distributed Generation Units. *IEEE Transactions on Industry Applications, 52*(6), 4656-4667. doi:10.1109/TIA.2016.2594231

Satheeshkumar, R., & Shivakumar, R. (2016). Ant Lion Optimization Approach for Load Frequency Control of Multi-Area Interconnected Power Systems. *Circuits and Systems, Vol.07No.09*, 27. doi:10.4236/cs.2016.79206

Shaw, B., Mukherjee, V., & Ghoshal, S. P. (2011). Seeker optimisation algorithm: application to the solution of economic load dispatch problems. *IET Generation, Transmission & Distribution, 5*(1), 81-91. doi:10.1049/iet-gtd.2010.0405

Shen, D., Jiang, T., Chen, W., Shi, Q., & Gao, S. (2015, 25-28 May 2015). *Improved chaotic gravitational search algorithms for global optimization.* Paper presented at the 2015 IEEE Congress on Evolutionary Computation (CEC).

Shi Y., E. R. C. (1998). *Parameter selection in particle swarm optimization. In: Porto V.W., Saravanan N., Waagen D., Eiben A.E. (eds) Evolutionary Programming VII* (Vol. 1447): Springer, Berlin, Heidelberg

Shibberu, K. B. a. Y. (2005). *Penalty functions and constrained optimization*.

Shih, M. Y., Conde, A., Leonowicz, Z., & Martirano, L. (2017). An Adaptive Overcurrent Coordination Scheme to Improve Relay Sensitivity and Overcome Drawbacks due to Distributed Generation in Smart Grids. *IEEE Transactions on Industry Applications, PP*(99), 1-1. doi:10.1109/TIA.2017.2717880

Shih, M. Y., Conde Enríquez, A., Hsiao, T.-Y., & Torres Treviño, L. M. (2017). Enhanced differential evolution algorithm for coordination of directional overcurrent relays. *Electric Power Systems Research, 143*, 365-375. doi:http://dx.doi.org/10.1016/j.epsr.2016.09.011

Shih, M. Y., Enríquez, A. C., Leonowicz, Z. M., & Martirano, L. (2016, 7-10 June 2016). *Mitigating the impact of distributed generation on directional overcurrent relay coordination by adaptive protection scheme.* Paper presented at the 2016 IEEE

16th International Conference on Environment and Electrical Engineering (EEEIC).

Simon, D. (2008). Biogeography-Based Optimization. *IEEE Transactions on Evolutionary Computation, 12*(6), 702-713. doi:10.1109/TEVC.2008.919004

Singh, M., Panigrahi, B. K., & Abhyankar, A. R. (2013a). Optimal coordination of directional over-current relays using Teaching Learning-Based Optimization (TLBO) algorithm. *International Journal of Electrical Power & Energy Systems, 50*(Supplement C), 33-41. doi:https://doi.org/10.1016/j.ijepes.2013.02.011

Singh, M., Panigrahi, B. K., & Abhyankar, A. R. (2013b). Optimal coordination of directional over-current relays using Teaching Learning-Based Optimization (TLBO) algorithm. *International Journal of Electrical Power & Energy Systems, 50*(0), 33-41. doi:http://dx.doi.org/10.1016/j.ijepes.2013.02.011

Singh, M., Panigrahi, B. K., Abhyankar, A. R., & Das, S. (2014). Optimal coordination of directional over-current relays using informative differential evolution algorithm. *Journal of Computational Science, 5*(2), 269-276. doi:http://dx.doi.org/10.1016/j.jocs.2013.05.010

Singh, N., & Singh, S. (2017). A Modified Mean Gray Wolf Optimization Approach for Benchmark and Biomedical Problems. *Evolutionary Bioinformatics, 13*, 1176934317729413. doi:10.1177/1176934317729413

Single input energizing measuring relays with dependent specified time. (1976). *IEC standard 60255-4*: IEC publication.

So, C. W., Li, K. K., Lai, K. T., & Fung, K. Y. (1997a, 25-27 Mar 1997). *Application of genetic algorithm for overcurrent relay coordination.* Paper presented at the Developments in Power System Protection, Sixth International Conference on (Conf. Publ. No. 434).

So, C. W., Li, K. K., Lai, K. T., & Fung, K. Y. (1997b, 11-14 Nov 1997). *Application of genetic algorithm to overcurrent relay grading coordination.* Paper presented at the Advances in Power System Control, Operation and Management, 1997. APSCOM-97. Fourth International Conference on (Conf. Publ. No. 450).

Srivastava, A., Tripathi, J. M., Krishan, R., & Parida, S. K. (2018). Optimal Coordination of Overcurrent Relays Using Gravitational Search Algorithm With DG Penetration. *IEEE Transactions on Industry Applications, 54*(2), 1155-1165. doi:10.1109/TIA.2017.2773018

Srivastava, A., Tripathi, J. M., Mohanty, S. R., & 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. doi:10.1080/15325008.2015.1117539

Storn, R., & Price, K. (1997). Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces. *Journal of Global Optimization, 11*(4), 341-359. doi:10.1023/a:1008202821328

Sueiro, J. A., Diaz-Dorado, E., Míguez, E., & Cidrás, J. (2012). Coordination of directional overcurrent relay using evolutionary algorithm and linear programming. *International Journal of Electrical Power & Energy Systems, 42*(1), 299-305. doi:http://dx.doi.org/10.1016/j.ijepes.2012.03.036

Sulaiman, M. H., Mustaffa, Z., Mohamed, M. R., & Aliman, O. (2015). Using the gray wolf optimizer for solving optimal reactive power dispatch problem. *Applied Soft Computing, 32*(0), 286-292. doi:http://dx.doi.org/10.1016/j.asoc.2015.03.041

Thangaraj, R., Pant, M., & Abraham, A. (2010). New mutation schemes for differential evolution algorithm and their application to the optimization of directional over-current relay settings. *Applied Mathematics and Computation, 216*(2), 532-544. doi:http://dx.doi.org/10.1016/j.amc.2010.01.071

Thangaraj, R., Pant, M., & Deep, K. (2010). Optimal coordination of over-current relays using modified differential evolution algorithms. *Engineering Applications of Artificial Intelligence, 23*(5), 820-829. doi:https://doi.org/10.1016/j.engappai.2010.01.024

The Institute of Electrical and Electronics Engineers, I. (1996). IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays: Power System Relaying Committee of the IEEE Power Engineering Society.

TheStarOnline. (2005, 14 January 2005). Major blackouts in Malaysia, Online newspaper. *The Star Online*. Retrieved from https://www.thestar.com.my/news/nation/2005/01/14/major-blackouts-in-malaysia/

Urdaneta, A. J., Nadira, R., & Perez Jimenez, L. G. (1988). Optimal coordination of directional overcurrent relays in interconnected power systems. *IEEE Transactions on Power Delivery, 3*(3), 903-911. doi:10.1109/61.193867

Urdaneta, A. J., Restrepo, H., Marquez, S., & Sanchez, J. (1996). Coordination of directional overcurrent relay timing using linear programming. *Power Delivery, IEEE Transactions on, 11*(1), 122-129. doi:10.1109/61.484008

Verma, O. P., Aggarwal, D., & Patodi, T. (2016). Opposition and dimensional based modified firefly algorithm. *Expert Systems with Applications, 44*, 168-176. doi:https://doi.org/10.1016/j.eswa.2015.08.054

Viawan, F. A., Karlsson, D., Sannino, A., & Daalder, J. (2006, 14-17 March 2006). *Protection Scheme for Meshed Distribution Systems with High Penetration of Distributed Generation.* Paper presented at the 2006 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources.

Wang, W., Li, Z., & Ma, Y. (2009, 8-11 Aug. 2009). *Application of backtracking algorithm in college dormitory assignment management.* Paper presented at the 2009 2nd IEEE International Conference on Computer Science and Information Technology.

Wei, Y., Ni, N., Liu, D., Chen, H., Wang, M., Li, Q., . . . Ye, H. (2017). An Improved Grey Wolf Optimization Strategy Enhanced SVM and Its Application in Predicting the Second Major. *Mathematical Problems in Engineering, 2017*, 12. doi:10.1155/2017/9316713

Wolpert, D. H., & Macready, W. G. (1997). No free lunch theorems for optimization. *IEEE Transactions on Evolutionary Computation, 1*(1), 67-82. doi:10.1109/4235.585893

Y. G. Painthakar, B., S.R. (2007). *Fundamentals of Power System Protection* (5th ed.): Prentice-Hall of India Private Limited, New Delhi.

Yang, X.-S., & Deb, S. (2014). Cuckoo search: recent advances and applications. *Neural Computing and Applications, 24*(1), 169-174. doi:10.1007/s00521-013-1367-1

Yang, X., & Suash, D. (2009, 9-11 Dec. 2009). *Cuckoo Search via Lévy flights.* Paper presented at the 2009 World Congress on Nature & Biologically Inspired Computing (NaBIC).

Zawbaa, H. M., Emary, E., Parv, B., & Sharawi, M. (2016, 24-29 July 2016). *Feature selection approach based on moth-flame optimization algorithm.* Paper presented at the 2016 IEEE Congress on Evolutionary Computation (CEC).

Zayandehroodi, H., Mohamed, A., Shareef, H., & Farhoodnea, M. (2012). A novel neural network and backtracking based protection coordination scheme for distribution system with distributed generation. *International Journal of Electrical Power & Energy Systems, 43*(1), 868-879. doi:https://doi.org/10.1016/j.ijepes.2012.06.061

Zeineldin, H. H., El-Saadany, E. F., & Salama, M. M. A. (2006). Optimal coordination of overcurrent relays using a modified particle swarm optimization. *Electric Power Systems Research, 76*(11), 988-995. doi:http://dx.doi.org/10.1016/j.epsr.2005.12.001

Zhan, H., Wang, C., Wang, Y., Yang, X., Zhang, X., Wu, C., & Chen, Y. (2016). Relay Protection Coordination Integrated Optimal Placement and Sizing of Distributed Generation Sources in Distribution Networks. *IEEE Transactions on Smart Grid, 7*(1), 55-65. doi:10.1109/TSG.2015.2420667

Zhang, Y., Li, Y., Xia, F., & Luo, Z. (2012). *Immunity-Based Gravitational Search Algorithm*, Berlin, Heidelberg.

Zhigang, L., Fan, Z., Zailin, G., & Xinyu, S. (2008, 25-27 June 2008). *The analysis of particle swarm optimization algorithm's convergence.* Paper presented at the 2008 7th World Congress on Intelligent Control and Automation.

Zhu, Y., Dai, C., & Chen, W. (2014). Seeker Optimization Algorithm for Several Practical Applications. *International Journal of Computational Intelligence Systems, 7*(2), 353-359. doi:10.1080/18756891.2013.864476