Overcurrent Relays Coordination Optimisation Methods in Distribution Systems for Microgrids: A Review

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Abstract

Electric power networks connected with multiple distributed generations (microgrids) require adequate protection coordination. In this paper, the overcurrent relay coordination concept in distribution system has been presented with details. In this available literature, the previous works on optimisation methods utilised for the coordination of over current relays; classification has been made based on the optimisation techniques, non-standard characteristics, new constraints that have been proposed for optimal coordination and dual setting protection schemes. Then a comprehensive review has been done on optimisation techniques including the conventional methods, heuristic and hybrid methods and the relevant issues have been addressed.

1   Introduction

Reliable operations of the power grid are becoming importance nowadays more than ever, due to the embedding of electric-powered technology in all human activities. Protection of the electric grid against interruptions caused by different faults occupies the priority of power system researchers concerns [1]. Planning of protection schemes accurately is required to guarantee reliability, speed and selectivity of protective relays to insulate the parts under faulted conditions from the rest of the network. Protection issues have become more complex with evolving of the distribution networks (DNs) toward the vision of distributed generations (DGs). Additionally, the growing of the DGs connections introduced extra challenges with the concept of micro-grids (MGs). To obtain the maximum advantages from these upcoming power generation technologies with maintaining the existing power system infrastructure, there are main protection issues required to be taken into considerations which are false tripping, binding tripping recloser malfunctions, binding, nuisance (sympathetic) and undesired islanding [2].
 Traditional distribution system is radial in nature. The protection of these networks is relatively simple protective devices such as overcurrent (OC) relays, fuses and reclosers [3]. An OC relay is a device that determines whether sending signal or not to open a circuit breaker by measuring the current which pass through it [4]. There are other relays kinds such as directional relays, definite time OC relays and distance relays. Yet, inverse time OC relay is extensively used and it is considered the most preferable type in protection system of

DNs because of their fine selectivity, economic advantages, simplicity and efficiency in installation and implementation [5]& [6]. In decades, for the distribution systems, obtaining costly effective and reliable performance adopt the OC scheme coordination amongst the inherited requirements. The OC relays utilised as a primary (p) as well as backup (b) protection respectively in the transmission and sub-transmission systems [7]. They work at a coordinated structure with a composed predesigned. As a rule, firstly, the primary OC relay isolates the fault in coordinated scheme, if this primary OC relay being unsuccessful to trip in the pre-designed time after a specific pre-calculated time known as Coordination Time Interval (CTI), the backup OC relay isolates the fault automatically. Fig.1 illustrates the coordination constraint between primary and backup relays. It considers a constraints problem beside both of the Plug Setting (PS) range and Time Dial Setting (TDS) range of relay. This problem is extremely complicated both in constraints set and in objective function (OF) [8].
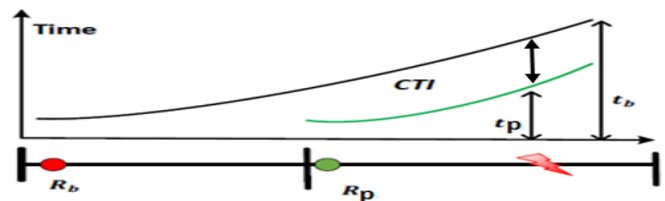

Fig.1: The of coordination constraint among primary (p) and backup (b) relay

2. Coordination of OC relays Formulation

2.1 Standard Relay Characteristic

Standard relay characteristics (relay characteristic curve) are used as a standard for adjusting the time OC relay functions. It can be classified into two main standards started in the IEEE standard [9]. Various institutes use curve constants, for example the International Electrotechnical Commission (IEC) [10], they are listed in Table.1 as following:

Stander	Curve	A	B	C
IEC	NI	0.14	0.02	0
	VI	13.5	2	0
	EI	80	2	0
IEE	NI	0.0515	0.02	0.114
	VI	19.61	2	0.491
	EI	28.2	2	0.1218

Table.1: IEC and IEEE standardised curves characteristic constants.

Normal inverse (NI), very inverse (VI), extremely inverse (EI) and (A, B, C) time curve characteristic constants.

The OC relay tripping time for a known short-circuit current (Isc) and pickup current (Ip) is calculated by using Equation (1), (2) defined by IEC and IEEE standards respectively.

$$t = \left[\frac{A}{\left(\frac{Isc}{Ip} \right)^B - 1} \right] \times TDS \dots \dots \dots (1)$$

$$t = \left[\frac{A}{\left(\frac{Isc}{Ip} \right)^B - 1} + C \right] \times TDS \dots \dots \dots (2)$$

2.2 Problem Formulation of Coordination:

2.2.1 Objective Function

The OC relays coordination problem relays in interconnected power systems, it is usually stated as a constrained optimisation problem, where the objective function (OF) is used to minimise the total operating time of the primary and backup relays [11]

$$OF = \sum_{i=1}^{m} t_{i,j}$$

Where $t_{i,j}$, indicates the operation time of the primary relay at i for near end fault and m is the primary relays numbers. The following constraints have achieved this objective [11] [12]:

2.2.2 Coordination criteria

$$t_b - t_p \geq CTI$$

Where t_p is the primary relay operating time for near end fault, while, t_b is the backup relay operating time, similarly for near end fault. Usually CTI selected as $(0.2s \leq CTI \leq 0.5s)$ [13]

2.2.3 Bounds on the relay setting operating time

The of bounds expression on TMS and PS are shown as following:

$$TMS_{min} \leq TMS_i \leq TMS_{max}$$

$$PS_{min} \leq PS_i \leq PS_{max}$$

Where TMS_{min} and TMS_{max} are the minimum and maximum TMS value, whereas PS_{min} and PS_{max} are in order of the minimum and maximum PS value of relay.

2.2.4 Bunds on the relay setting operating time

A minimum amount of time is required to operate the relay and likewise it should not take large time to operate. Mathematically, it can be stated as,

$$t_{min} \leq t_{op} \leq t_{max}$$

Where t_{min} and t_{max} are the relay R_i minimum and maximum operating time.

3. Over Current Relay Coordination Methods

In the past four decades, there are a considerable number of methods have been proposed for the overcurrent relays coordination. According to this review, these methods can be illustrated and divided into optimisation techniques, new constraints for optimal coordination, non- standard characteristics (NSCs) and dual setting protection schemes. This classification is illustrated in fig.2 as following:
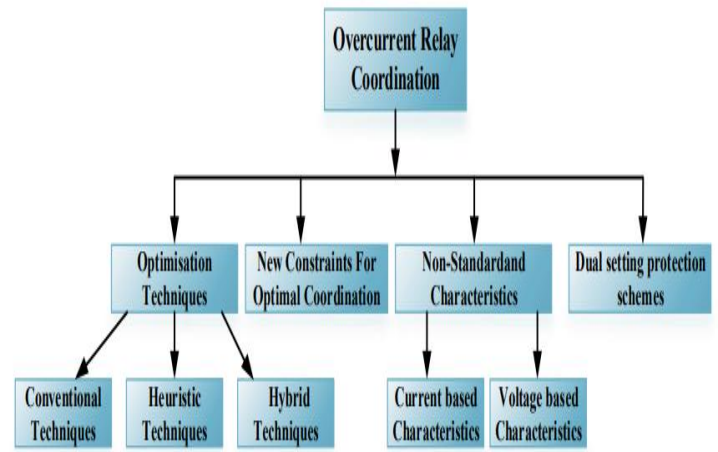

Fig.2: Over Current Relay Coordination Methods

3 .1 Optimisation Techniques

Normally, obtaining the relays optimum settings is considered the goal of optimisation-based approaches. In this approach three main techniques which are: Conventional techniques, heuristic techniques and hybrid techniques, it will be in details as following:

3.1.1 Conventional Methods Optimisation Techniques Applications

In overcurrent relays coordination, a range of techniques exist. The approaches could be classified into three classes which include: optimisation method, trial and error, and topological analysis techniques [14] [15] [16] [17] [18]. Despite the slow convergence frequency and a large number of needed iterations to attaining a suitable relay setting, the trial and error technique was still used [19] [20] To lower the iteration number needed for the process of coordination, a method was recommend for breaking each loop known as breakpoint and identify the first relays at each of these points.

Identifying the breakpoints is an essential section for initiating the process of the coordination. Topological methods that are comprised of graph and functional theory are applied for identifying the break points [20]. In the functional method, a set of functional dependencies is used to formulate the relay

settings constraints in the functional approach. Other topological analysis that are in linear graph theory are stretched to analysis every simple network loop in both directions minding the least set of breakpoints as well as the backup and basic relay pairs. This method provided the best solution for the option settings included though not maximum in any strict sense. Implying that, the relay's TDS or TMS are increased. Besides, because of the system complexity, error and trial method and topological analysis are not optimal and are time consuming. According to [21], the previous study about the directional overcurrent relays consist of three categories: optimization technique, curve fitting technique, and graph theoretical technique. The curve fitting approaches are applied in the identification of the finest function for representing data. The curve fitting techniques are applied in relay properties for mathematically analysing through polynomial [22] [23]. The graph theoretical techniques also reported as the second category [24]. The system framework is applied for analysis the data on breakpoints minimum set, line directionality for directional relays, sequence for setting relay, and the entire basic or backup relays. Figure.3 below indicates the conventional or classical technique applied for coordination of the finest overcurrent relay.
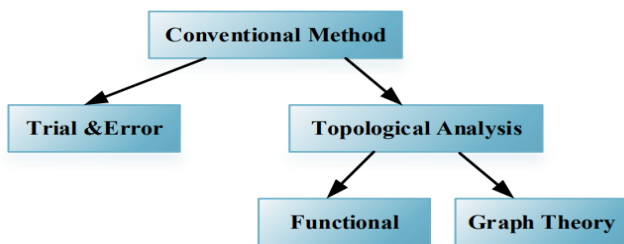

Fig.3: Approach of the Conventional Methods

Generally, the optimisation method overwhelmed the conventional technique that had relays in sequential order prior to been considered for coordination [25]. It is popular amongst scholars because of its benefits. Moreover, in optimisation approach, determining the breakpoints set is not necessary. The first use of the optimisation theory during directional overcurrent relay coordination was Conventional Method Trial & Error Topological Analysis Functional Graph Theory [26]. Whereby, the calculation of TSM values was done through the Linear programming (LP) model, simplex technique for pickup current stated values, Ip. Some scholars applied the non-linear programming in optimising approach in order to find a solution for the coordination problem though the method was time consuming and complex [27]. This is because the non-linear programming method, depends on the TMS, Ip, and relay properties, optimized simultaneously. In [26], [28] and [29], they formulate the relay coordination problem as a mixed integer non-linear programming (MINLP) and through General Algebraic Modelling System (GAMS) software they solve it. But, the application of binary variables to consider the discrete pickup currents, Ips heightens the coordination problem complexity [21]. Following the technique's complexity, the overcurrent relays coordination is often conducted through linear programming (LP) approaches like

the two-phase Simplex and Simplex, dual Simplex techniques [30], [31], [32], [21] and [28]. The limitation of these method is that it depends on first guess and could be trapped in the local minimum [33]. The assumption in these techniques is that the pickup current, Ip settings is to be known and, in its TDS, or TMS, the operation time for every relay is linear function.

Bedekar et. al in [34], recommended Big-M (penalty) technique for determining the overcurrent relays TMS whereby assuming that the PS is fixed and known. This approach depends on the simplex algorithm applied to determine the optimal solution in linear programming questions. To obtain a first primary feasible solution referred as IBFS, artificial variables are introduced in the objective function. In addition, in [35], [36] and [37] Bedekar et. al suggested Simplex, two-phase Simplex, and dual Simplex techniques for solving the problem of directional overcurrent relay in ring fed system of distribution. Following the recommended LP methods and Big-M (penalty) techniques, the paper in [38] made a comparison of the four techniques and it was indicated that in comparison to others, the dual-Simplex technique was the most suitable one. The authors stated that the calculations number for each iteration within dual-Simplex technique is lower than the other three technique. Nevertheless, [15] explained that even when LP methods are simple and converge easily to optimal solutions, just the values of TSM could be optimised rather than pickup current, they have to select Ip through experience of load and fault data. Normally, this does not offer a global optimum solution or answer of the issue. Therefore, the application of these LP methods contains boundaries in relation of low constraint number [39]

3.1.2 Heuristic Techniques

Currently, evolutionary and heuristic formulation depending on methods like genetic algorithm (GA) was successfully implemented for optimal coordination overcurrent relay to reduce the operation time of relays and reduce miscoordination problem [40]. For particle swarm optimisation (PSO) in the formulation of the optimal relay settings, [41] confirmed that PSO is more suitable for dealing with miscoordination issues for both discrete and continuous PSM and TSM instead of GA though. In relation to the enhanced convergence properties, some GA improvements [41] like progressive GA [28]. They have adopted Evolutionary programming [42] and various types of DE techniques like the adaptive (ADE) algorithm [43] and opposition-based chaotic DE algorithm in order to obtain the optimum setting of relays by the improvements of discrete values of decision variables [44]. [19] conducted an evaluation on the five varied versions of modified differential evolution (MDE) in order to comparatively judge their performance in offering a solution to the relay coordination problem. In these techniques, the local optima influence the solution because of the constant scaling components. [45] [20] made an attempt to attain the OC relays coordination through the improved PSO methods. To acquire the OC relays optimum coordination in the ring-based power systems, [46] utilised the Teaching learning-based optimization (TLBO) algorithm. Then, [47] recommended an advanced group search optimisation algorithm in the DO relays' coordination. In addition, in order

to deal with the DO relay coordination influenced by the dynamic alteration in the network topology and Ant colony optimisation (ACO) have been applied in solving the coordination problem in OC relays [48]. [49] suggested a new seeker optimisation method for the DO relays coordination. But, most of the past techniques have a major deficiency that is the convergence threat in the local optima. Firefly algorithm (FA) was selected to obtain an optimised OC relay function [50]. In the optimisation, the FA performance is related to a random value of Gaussian distribution that results to moderate trapping and convergence during the local optimising point. Thus, an advanced adaptive modified FA (AMFA) is suggested to determine the OC relays optimal coordination. AMFA amends the FA through the manner of investigation in the search of the OC relays' optimum coordination and growing the speed in the convergence [51]. An ant lion optimiser (ALO) is applied to solve coordination problem as a constrained optimisation problem. In the distribution system, the (OF) was targeting a minimum OT of OC relays [52]. A new optimisation technique called Water cycle algorithm (WCA) is presented to deal with the problem of overcurrent relays coordination. To define the best OC relay setting, the adapted problem is mathematically formulated [39].

3.1.3 Hybrid Techniques

Moreover, most of hybrid structures have been adopted for improving the performance obtained in resolving the problem of OC relay coordination. Within those techniques, non-dominated sorting GA-II and hybrid GA [28] [53], have been exercised to lower coordination times of backup/basic relay pairs and relay operating times. [29] [54] made a contribution toward obtaining the global optimum values for PS and TMS through Hybrid (GA-NLP) technique and recommended Continuous Genetic Algorithm (CGA) in order to lower the function time of relays and eliminate the mal-operation of the relays. [55] proposed Particle Swarm Optimization (NM-PSO) and a hybrid Nelder-Mead Simplex search method. This technique is applied to enhance the efficacy of the PSO for feasibility, fast convergence, and computation speed. A hybrid gravitational search algorithm and sequential quadratic programming (GSA-SQP) has been introduced such one of the solutions of the OC relays coordination problem; it has been tested and evaluated on various test systems [56]. A Hybrid particle swarm optimisation and moth- flame Optimisation (PSOMFO) has been combined MFO for exploration phase and PSO for exploitation phase; the results seem to be effective compared to standard MFO and PSO algorithm [57]. Utilising the setting groups concept, an APS is proposed to rise the reliability of the system. For network topology changes, a hybrid linear programming (LP) and genetic algorithm (GA) method is used to solve the problem. Thus, classifies the network topology changes scenarios into a limited number of setting groups and the LP algorithm optimally coordinates the overcurrent relays within the setting groups, the GA, in a near-optimal manner [58]. There is a new proposed algorithm is using hybrid whale optimization algorithm and grey wolf optimiser (HWGO); it applied for enhancing the reliability and performance of the conventional whale optimisation

algorithm (WOA), the result have appeared the ability of HWGO algorithm to make a progress of the traditional WOA and overcomes its drawbacks in terms of overcurrent coordination problem [59].

3.2 Non-Standard Characteristics (N-SCs)

This part focuses mainly on providing details on the researches that targets construction of N-SCs so that the protection coordination can be attained in the power systems. These untraditional techniques are classified as methods which would contain electrical magnitudes.

3.2.1 (N-SCs) with Electrical Magnitudes:

Previously, the relays which were applied to detect and clear a problem based only on the liability current value. Nevertheless, currently, the voltage value can be applied to establish the liability section of the power system because of the fact that OC relays is generally more accessible and capable of determining both voltage and current values by the fact that, they are linked to current via voltage transformers. According to the past study, these OC relays features offer a chance for the use of N-SCs that are created not just through considering the current as well as the voltage value [60] [61] [62].. This section, the research compared attaining of relay coordination with respect to the different integrations of determined voltage and current values analysed.

3.2.1.1 Characteristics Based on Current

There is still a possibility to produce N-SCs by merely depending on the current measurement, though SCs readily utilizes the current. Researches applied current in varied approaches obtained from the SCs are reviewed in this subsection. Industrial power systems comprise of very rich environment with respect to the protective devices. Many protective devices types like the fuses, digital relays, and electromechanical relays are observed in a similar industrial power system. Though, in this highly diverse environment, coordinating various forms of protective devices like the relay-fuse is a complex task when utilising standard techniques. The N-SC is proposed to tackle very complex coordination issues within the industrial power system [63]. In this property, the assumption is that a value shifts dynamically with respect to the measured current value rather than being constant. In [63] the characteristic equations are provided in (3) and (4). Nevertheless, it is essential to ensure that A (Isc) function is determined with respect to the specific protection problem. In (3) and (4) they represent the effect of the shifting fault current on N-SC property.

$$A(Isc) = A . e^{-Isc/C} \dots \dots \dots (3)$$

$$t = \left[\frac{A(Isc)}{\left(\frac{Isc}{Ip}\right)^B - 1} \right] \times TDS \dots \dots \dots \dots (4)$$

Other researches targeted obtaining N-SCs depending on the determined current presented in [64] [65], that integrated the non-standard approaches and adaptive relay concept. They took the pickup current as a load current function for these investigations (Ip (IL)). Though, rather than applying an explicit equation, in [23] they presented curve fitting approach depending on a polynomial equation, and it was used in a software that was specifically established for applications of relay coordination. Although, the structure provided as an output equation through the equation was very complex and did not require setting automatic and parameters coordination, it was a superior property for this approach.

3.2.1.2 Characteristics Based on Voltage

In the presence of DGs units, there are several modified OC relays curves have been proposed by various researchers to reduce their operation time that in the non-standard voltage based characteristic curves. Table.2 illustrates these modified OC relays curves. In table 2, the Eq. (5) introduced the voltage value into the IEC standard property equation as a multiplier that lowered the relay OT in every potential fault condition, which unit value of the determined voltage (V_f) and K is a new constant [62]. (6) provides the properties of the equation formed in [66], whereby the voltage parameter was applied in enhancing the coordination of the fuse-relay in the DG presence. An identical technique in relation to applying magnitudes of voltage is indicated in [67], the characteristics presented in (7). In (8) and (9) an alternative kind of voltage depended property is presented in [68]. The construction of the N-SC targeted to enhance recloser-fuse coordination in a system of distribution inclusive of DG units. A varying voltage-based N-SC, that is provided in (10), was indicated in [69]&[70]. The characteristic equation was identical to (5), but for the use of the voltage the logarithmic function is applied. In [71] an alternative method by the voltage measurement using a logarithmic function is suggested. (11) provides the characteristic equation. This characteristic equation excludes TDS setting, and hence, eradicates inheritance of the limitation of growing OT in the direction of the source. Furthermore, through adjusting A, B, and C within the equation, ensures the coordination. The recommended property lowers the effect of the DG and offers a comparatively low OTs, though; there is still a need for further study on the big dimensional power network because of the growing variables numbers to be optimised.

Ref	Modified Operation Time Curve of OC Relays
[62]	$t = \left(\dfrac{1}{e^{(1-Vf)}}\right)^k \left[\dfrac{A}{\left(\frac{Isc}{Ip}\right)^B - 1}\right] \times TDS. \quad (5)$
[66]	$t = \left(\dfrac{Vf}{e^{k-Vf}}\right)\left[\dfrac{A}{\left(\frac{Isc}{Ip}\right)^B - 1}\right] \times TDS \dots (6)$

Ref	Existing OC relays non-standard characteristic curves
[67]	$t = TDS.\dfrac{(Vf)^k}{e^{Vf}}\left[\dfrac{A}{(\ln(Vn\frac{Isc}{Vf}))^B - (\ln(Vn\frac{Iset}{Vset}))^B} + C\right] + D \dots (7)$
[68]	$A = Vf.(1 - Vf) \dots (8)$ $t = A.\left[\dfrac{1}{1-(\log Vf)^C} + 0.121\right].TDS \dots (9)$
[69, 70]	$t = \left(\dfrac{1}{1-(\log Vf)^C}\right)^k \left[\dfrac{A}{\left(\frac{Isc}{Ip}\right)^B - 1}\right] \dots (10)$
[71]	$t = \dfrac{\log(Vf+A)}{M^B - 1} + C \dots (11)$

Table.2: Existing OC relays non-standard characteristic curves

3.3 New Constraints for Optimal Coordination

Most authors aim at including new constraints for optimal OC relays coordination. In [72] the author includes a novel constraint with respect to the operational status of variables in the distributed system within DG. [73] [74] suggested other constraints taking into consideration transient stability [75], fault current direction [76], and OCR coordination with distance protection scheme. Additionally, in [73] the author introduced a constraint considering the parameters of entire OC relay characteristics [77] and constraint in consideration of single outage contingency[N−1] [78]. A constraint deliberates fault ride through by the necessities for transmission level interconnected wind parks in [79], and varying network topologies in [28] had been recommended. A comparison among the performance of several objective functions (FOs) has been made and evaluated on 30-bus system (IEEE standard) [80]. All the types of short-circuit contributions in optimisation of OC relay coordination problem have been taken into consideration in [81]. A new constraint reduction for the distribution system with high penetration of the DGs has been proposed, which based on optimal relay coordination method. The independent settings for different feeder zones have been determined by the proposed method, where if mode gets changed there is no need of re-optimisation for new TDS [6]. For different microgrid topologies, a novel constraint represented the plug setting multiplier operating region in industrial OC relay curves had been investigated and verified [82].

3.4 Dual setting protection schemes

Contrary to the conventional OC relays, both of the primary and backup functionalities, respectively are provided by a single OC relay unit dual-setting. Therefore, the programming for every OC relay dual-setting is in two directions that is, reverse/backup and forward/primary, denoted by "fw/p" and "rv/b", accordingly. Every direction is functioned independently; thus, there are few interconnected coordination

constraints are stress-free. These properties lead to an enhanced performance in decreasing the total of relays operation time. However, research focus was devoted to the conventional DOC relays, very few studies have been conducted on dual-setting DOC relays. In the initial trial in [83], dual-setting DOC relays application was suggested for the protection of the radial distribution networks. In DG-mixed networks, it is noteworthy that regardless of employing DOC relays to tackle the dual-directional power flow, the working time is remaining prolonged. Through raising the penetration of DG, the coordination problem difficulty deepens that leads to certain increased working time for relays. Consequently, using dual-setting relays is expected that due to their ability to reduce the protection operations time and eliminate those challenges. In a recent attempt, the dual-setting OCRs utilising was contemplated for the distribution networks meshed protection that connected with several source [84]. In [85] the dual-setting OC relays were deployed for safeguarding a micro-grid with a capacity to function in both islanded and grid-connected modes. For all of the preceding researches, a significant decrease in the relay's life time is recorded. Though, the conventional relays were completely replaced with the dual-setting OC relays without considering the new scheme's economic burden. Expectedly, dual-setting OC relays implementation sensibly lowers the working time in the initial stage of the replacement levels. But, the decrease in the working time accumulates with increase in the penetration of dual-setting OC relays. The past researches ignored such a crucial aspect because the entire relays were expected to be dual-setting OC relays. This occurs when; a maximum relay number together with the traditional ones can provide a rapid protection operation in a cost-effective way [86]. There is a model of multi-objective optimisation proposed which goals at minimising the relay total operating time through replacement level of traditional OC relays with an optimal number of dual-setting OC relays [87]

Conclusion:

A comprehensive review on OC relay coordination has been conducted and presented in this paper. For the past four decades, a considerable number of methods and techniques has been proposed and implemented to face present day requirements. This paper has collected various optimisation methods in general seem to be reliable and effective. This review introduced many authors' researcher work on the techniques utilised in coordination of the OC relay. Some of the researches have chosen non-standard and user-defined characteristics technique to solve OC relay coordination problems and they have developed several equations to obtain the relays optimal coordination. While, some of them have added new constraints for optimal OC relay coordination. Despite, the conventional OC relays have been paid a great research attention, there are some researches head for dual-setting OC relays to reduce the relays total operation time.

References:

[1]   W. Yuan, L. Zhao, and B. Zeng, "Optimal power grid protection through a defender–attacker–defender model," *Reliability Engineering and System Safety,* vol. 121, pp. 83-89, 2014, doi: 10.1016/j.ress.2013.08.003.

[2]   V. A. Papaspiliotopoulos, G. N. Korres, V. A. Kleftakis, and N. D. Hatziargyriou, "Hardware-In-the-Loop Design and Optimal Setting of Adaptive Protection Schemes for Distribution Systems With Distributed Generation," *IEEE Transactions on Power Delivery,* vol. 32, no. 1, pp. 393-400, 2017, doi: 10.1109/TPWRD.2015.2509784.

[3]   A. Srivastava, J. M. Tripathi, R. Krishan, and S. K. Parida, "Optimal Coordination of Overcurrent Relays Using Gravitational Search Algorithm With DG Penetration," *IEEE Transactions on Industry Applications,* vol. 54, no. 2, pp. 1155-1165, 2018, doi: 10.1109/TIA.2017.2773018.

[4]   D. S. Alkaran, M. R. Vatani, M. J. Sanjari, G. B. Gharehpetian, and A. H. Yatim, "Overcurrent Relays Coordination in Interconnected Networks Using Accurate Analytical Method and Based on Determination of Fault Critical Point," *IEEE Transactions on Power Delivery,* vol. 30, no. 2, pp. 870-877, 2015, doi: 10.1109/TPWRD.2014.2330767.

[5]   R. H. Lasseter, "Smart Distribution: Coupled Microgrids," *Proceedings of the IEEE,* vol. 99, no. 6, pp. 1074-1082, 2011, doi: 10.1109/JPROC.2011.2114630.

[6]   E. Purwar, D. N. Vishwakarma, and S. P. Singh, "A Novel Constraints Reduction-Based Optimal Relay Coordination Method Considering Variable Operational Status of Distribution System With DGs," *IEEE Transactions on Smart Grid,* vol. 10, no. 1, pp. 889-898, 2019, doi: 10.1109/TSG.2017.2754399.

[7]   F. A. Albasri, A. R. Alroomi, and J. H. Talaq, "Optimal Coordination of Directional Overcurrent Relays Using Biogeography-Based Optimization Algorithms," *IEEE Transactions on Power Delivery,* vol. 30, no. 4, pp. 1810-1820, 2015, doi: 10.1109/TPWRD.2015.2406114.

[8]   L. G. Perez and A. J. Urdaneta, "Optimal coordination of directional overcurrent relays considering definite time backup relaying," *IEEE Transactions on Power Delivery,* vol. 14, no. 4, pp. 1276-1284, 1999, doi: 10.1109/61.796218.

[9]   G. Benmouyal *et al.*, "IEEE standard inverse-time characteristic equations for overcurrent relays," *IEEE Transactions on Power Delivery,* vol. 14, no. 3, pp. 868-872, 1999.

[10]   E. Relay-Part, "3: single input energizing quantity measuring relay with dependent or independent time," *IEC Standard,* vol. 60255, no. 3, 1989.

[11]   B. Chattopadhyay, M. S. Sachdev, and T. S. Sidhu, "An on-line relay coordination algorithm for adaptive protection using linear programming technique," *IEEE Transactions on Power Delivery,* vol. 11, no. 1, pp. 165-173, 1996, doi: 10.1109/61.484013.

[12]   H. Zeienldin, E. F. El-Saadany, and M. A. Salama, "A novel problem formulation for directional overcurrent relay coordination," 2004: IEEE, pp. 48-52, doi: 10.1109/LESCPE.2004.1356265.

[13]   P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum coordination of overcurrent relays in distribution system using genetic algorithm," 2009: IEEE, pp. 1-6, doi: 10.1109/ICPWS.2009.5442716.

[14]   M. Barzegari, S. M. T. Bathaee, and M. Alizadeh, "Optimal coordination of directional overcurrent relays using harmony search algorithm," 2010: IEEE, pp. 321-324, doi: 10.1109/EEEIC.2010.5489935.

[15]   M. Ezzeddine and R. Kaczmarek, "A novel method for optimal coordination of directional overcurrent relays considering their available discrete settings and several operation characteristics," *Electric Power Systems Research,* vol. 81, no. 7, pp. 1475-1481, 2011, doi: 10.1016/j.epsr.2011.02.014.

[16]   K. Tuitemwong and S. Premrudeepreechacharn, "Expert system for protection coordination of distribution system with distributed generators," *International Journal of Electrical Power and Energy Systems,* vol. 33, no. 3, pp. 466-471, 2011, doi: 10.1016/j.ijepes.2010.10.009.

[17]   V. S. Chaudhari, V. Upadhyay, and G. Ahemedabad, "Coordination of overcurrent relay in interconnected power system protection," in *National Conference on Recent Trends in Engineering & Technology*, 2011.

[18] J. Gholinezhad, K. Mazlumi, and P. Farhang, "Overcurrent relay coordination using MINLP technique," in *2011 19th Iranian Conference on Electrical Engineering*, 2011: IEEE, pp. 1-6.

[19] R. Thangaraj, M. Pant, and K. Deep, "Optimal coordination of over-current relays using modified differential evolution algorithms," *Engineering Applications of Artificial Intelligence*, vol. 23, no. 5, pp. 820-829, 2010.

[20] M. M. Mansour, S. F. Mekhamer, and N. E. S. El-Kharbawe, "A Modified Particle Swarm Optimizer for the Coordination of Directional Overcurrent Relays," *IEEE Transactions on Power Delivery*, vol. 22, no. 3, pp. 1400-1410, 2007, doi: 10.1109/TPWRD.2007.899259.

[21] D. Birla, R. P. Maheshwari, and H. O. Gupta, "Time-overcurrent relay coordination: a review," *International Journal of Emerging Electric Power Systems*, vol. 2, no. 2, 2005.

[22] H. Smooolleck, "A simple method for obtaining feasible computational models for time characteristics for industrial power system protective," *Electric Power Systems Research*, vol. 2, pp. 129-134, 1979.

[23] "Computer representation of overcurrent relay characteristics," *IEEE Transactions on Power Delivery*, vol. 4, no. 3, pp. 1659-1667, 1989, doi: 10.1109/61.32656.

[24] L. Jenkins, H. P. Khincha, S. Shivakumar, and P. K. Dash, "An application of functional dependencies to the topological analysis of protection schemes," *IEEE Transactions on Power Delivery*, vol. 7, no. 1, pp. 77-83, 1992, doi: 10.1109/61.108892.

[25] R. Mohammadi, H. A. Abyaneh, H. M. Rudsari, S. H. Fathi, and H. Rastegar, "Overcurrent Relays Coordination Considering the Priority of Constraints," *IEEE Transactions on Power Delivery*, vol. 26, no. 3, pp. 1927-1938, 2011, doi: 10.1109/TPWRD.2011.2123117.

[26] A. J. Urdaneta, R. Nadira, and L. G. Perez Jimenez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Transactions on Power Delivery*, vol. 3, no. 3, pp. 903-911, 1988, doi: 10.1109/61.193867.

[27] H. A. Abyaneh, M. Al-Dabbagh, H. K. Karegar, S. H. H. Sadeghi, and R. A. J. Khan, "A new optimal approach for coordination of overcurrent relays in interconnected power systems," *IEEE Transactions on Power Delivery*, vol. 18, no. 2, pp. 430-435, 2003, doi: 10.1109/TPWRD.2002.803754.

[28] A. S. Noghabi, J. Sadeh, and H. R. Mashhadi, "Considering Different Network Topologies in Optimal Overcurrent Relay Coordination Using a Hybrid GA," *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp. 1857-1863, 2009, doi: 10.1109/TPWRD.2009.2029057.

[29] P. P. Bedekar and S. R. Bhide, "Optimum Coordination of Directional Overcurrent Relays Using the Hybrid GA-NLP Approach," *IEEE Transactions on Power Delivery*, vol. 26, no. 1, pp. 109-119, 2011, doi: 10.1109/TPWRD.2010.2080289.

[30] V. Rashtchi, J. Gholinezhad, and P. Farhang, "Optimal coordination of overcurrent relays using Honey Bee algorithm," 2010: IEEE, pp. 401-405, doi: 10.1109/ICUMT.2010.5676606.

[31] F. Razavi, H. A. Abyaneh, M. Al-Dabbagh, R. Mohammadi, and H. Torkaman, "A new comprehensive genetic algorithm method for optimal overcurrent relays coordination," *Electric Power Systems Research*, vol. 78, no. 4, pp. 713-720, 2008, doi: 10.1016/j.epsr.2007.05.013.

[32] M. Singh, B. K. Panigrahi, and A. R. Abhyankar, "Optimal overcurrent relay coordination in distribution system," 2011: IEEE, pp. 1-6, doi: 10.1109/ICEAS.2011.6147214.

[33] Z. Moravej, M. Jazaeri, and M. Gholamzadeh, "Optimal coordination of distance and over-current relays in series compensated systems based on MAPSO," *Energy Conversion and Management*, vol. 56, pp. 140-151, 2012, doi: 10.1016/j.enconman.2011.11.024.

[34] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum time coordination of overcurrent relays in distribution system using Big-M (penalty) method," *WSEAS Transactions on Power Systems*, vol. 4, no. 11, pp. 341-350, 2009.

[35] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Coordination of overcurrent relays in distribution system using linear programming technique," 2009: IEEE, pp. 1-4.

[36] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum Coordination of Overcurrent Relays in Distribution System Using

Dual Simplex Method," 2009: IEEE, pp. 555-559, doi: 10.1109/ICETET.2009.164. [37] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum Coordination of Overcurrent Relay Timing Using Simplex Method," *Electric Power Components and Systems*, vol. 38, no. 10, pp. 1175-1193, 2010, doi: 10.1080/15325001003652900.

[38] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Determining optimum TMS and PS of overcurrent relays using linear programming technique," 2011: IEEE, pp. 700-703, doi: 10.1109/ECTICON.2011.5947936.

[39] A. A. El-Fergany and H. M. Hasanien, "Water cycle algorithm for optimal overcurrent relays coordination in electric power systems," *Soft Computing*, 2019, doi: 10.1007/s00500-019-03826-6.

[40] C. W. So, K. K. Li, K. T. Lai, and K. Y. Fung, "Application of genetic algorithm for overcurrent relay coordination," London, 1997: IEE, pp. 66-69, doi: 10.1049/cp:19970030.

[41] H. Zeineldin, E. El-Saadany, and M. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Electric Power Systems Research*, vol. 76, no. 11, pp. 988-995, 2006.

[42] C. W. So and K. K. Li, "Overcurrent relay coordination by evolutionary programming," *Electric Power Systems Research*, vol. 53, no. 2, pp. 83-90, 2000, doi: 10.1016/S0378-7796(99)00052-8.

[43] J. Moirangthem, K. Krishnanand, S. S. Dash, and R. Ramaswami, "Adaptive differential evolution algorithm for solving non-linear coordination problem of directional overcurrent relays," *IET Generation, Transmission & Distribution*, vol. 7, no. 4, pp. 329-336, 2013.

[44] T. R. Chelliah, R. Thangaraj, S. Allamsetty, and M. Pant, "Coordination of directional overcurrent relays using opposition based chaotic differential evolution algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 55, pp. 341-350, 2014.

[45] 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, no. 11, pp. 988-995, 2006, doi: 10.1016/j.epsr.2005.12.001.

[46] M. Singh, B. Panigrahi, and A. Abhyankar, "Optimal coordination of directional over-current relays using Teaching Learning-Based Optimization (TLBO) algorithm," *International Journal of Electrical Power & Energy Systems*, vol. 50, pp. 33-41, 2013.

[47] M. Alipour, S. Teimourzadeh, and H. Seyedi, "Improved group search optimization algorithm for coordination of directional overcurrent relays," *Swarm and Evolutionary Computation*, vol. 23, pp. 40-49, 2015.

[48] M. Y. Shih, C. A. C. Salazar, and A. C. Enríquez, "Adaptive directional overcurrent relay coordination using ant colony optimisation," *IET Generation, Transmission & Distribution*, vol. 9, no. 14, pp. 2040-2049, 2015.

[49] T. Amraee, "Coordination of Directional Overcurrent Relays Using Seeker Algorithm," *IEEE Transactions on Power Delivery*, vol. 27, no. 3, pp. 1415-1422, 2012, doi: 10.1109/TPWRD.2012.2190107.

[50] R. Benabid, M. Zellagui, A. Chaghi, and M. Boudour, "Application of firefly algorithm for optimal directional overcurrent relays coordination in the presence of IFCL," *International Journal of Intelligent Systems and Applications*, vol. 6, no. 2, pp. 44-53, 2014.

[51] A. Tjahjono *et al.*, "Adaptive modified firefly algorithm for optimal coordination of overcurrent relays," *IET Generation, Transmission & Distribution*, vol. 11, no. 10, pp. 2575-2585, 2017.

[52] A. Y. Hatata and A. Lafi, "Ant Lion Optimizer for Optimal Coordination of DOC Relays in Distribution Systems Containing DGs," *IEEE Access*, vol. 6, pp. 72241-72252, 2018, doi: 10.1109/ACCESS.2018.2882365.

[53] F. B. Bottura, W. M. S. Bernardes, M. Oleskovicz, and E. N. Asada, "Setting directional overcurrent protection parameters using hybrid GA optimizer," *Electric Power Systems Research*, vol. 143, pp. 400-408, 2017, doi: 10.1016/j.epsr.2016.09.017.

[54] P. P. Bedekar and S. R. Bhide, "Optimum coordination of overcurrent relay timing using continuous genetic algorithm," *Expert Systems With Applications*, vol. 38, no. 9, pp. 11286-11292, 2011, doi: 10.1016/j.eswa.2011.02.177.

[55] A. Liu and M.-T. Yang, "Optimal Coordination of Directional Overcurrent Relays Using NM-PSO Technique," 2012, no.

Conference Proceedings: IEEE, pp. 678-681, doi: 10.1109/IS3C.2012.176. [56] J. Radosavljević and M. Jevtić, "Hybrid GSA-SQP algorithm for optimal coordination of directional overcurrent relays," *IET Generation, Transmission & Distribution,* vol. 10, no. 8, pp. 1928-1937, 2016, doi: 10.1049/iet-gtd.2015.1223.

[57] R. Bhesdadiya, I. N. Trivedi, P. Jangir, A. Kumar, N. Jangir, and R. Totlani, "A novel hybrid approach particle swarm optimizer with moth-flame optimizer algorithm," in *Advances in Computer and Computational Sciences*: Springer, 2017, pp. 569-577.

[58] R. M. Chabanloo, M. Safari, and R. G. Roshanagh, "Reducing the scenarios of network topology changes for adaptive coordination of overcurrent relays using hybrid GA–LP," *IET Generation, Transmission & Distribution,* vol. 12, no. 21, pp. 5879-5890, 2018, doi: 10.1049/iet-gtd.2018.5810.

[59] A. Korashy, S. Kamel, F. Jurado, and A.-R. Youssef, "Hybrid Whale Optimization Algorithm and Grey Wolf Optimizer Algorithm for Optimal Coordination of Direction Overcurrent Relays," *Electric Power Components and Systems,* pp. 1-15, 2019, doi: 10.1080/15325008.2019.1602687.

[60] M. Dewadasa, A. Ghosh, G. Ledwich, and M. Wishart, "Fault isolation in distributed generation connected distribution networks," *IET Generation, Transmission & Distribution,* vol. 5, no. 10, p. 1053, 2011, doi: 10.1049/iet-gtd.2010.0735.

[61] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal Coordination of Directional Overcurrent Relays Using a New Time-Current-Voltage Characteristic," *IEEE Transactions on Power Delivery,* vol. 30, no. 2, pp. 537-544, 2015, doi: 10.1109/TPWRD.2014.2341666.

[62] N. Bayati, A. Dadkhah, S. H. H. Sadeghi, B. Vahidi, and A. E. Milani, "Considering variations of network topology in optimal relay coordination using time-current-voltage characteristic," 2017, no. Conference Proceedings: IEEE, pp. 1-5, doi: 10.1109/EEEIC.2017.7977810.

[63] O. Arreola Soria, A. Conde Enríquez, and L. A. Trujillo Guajardo, "Overcurrent relay with unconventional curves and its application in industrial power systems," *Electric Power Systems Research,* vol. 110, pp. 113-121, 2014, doi: 10.1016/j.epsr.2013.12.012.

[64] A. C. Enríquez, E. Vázquez-Martínez, and H. J. Altuve-Ferrer, "Time overcurrent adaptive relay," *International Journal of Electrical Power and Energy Systems,* vol. 25, no. 10, pp. 841-847, 2003, doi: 10.1016/S0142-0615(03)00059-0.

[65] A. Conde and E. Vázquez, "Functional Structure for Performance Improvement of Time Overcurrent Relays," *Electric Power Components and Systems,* vol. 35, no. 3, pp. 261-278, 2007, doi: 10.1080/15325000600978635.

[66] S. Jamali and H. Borhani-Bahabadi, "Recloser time–current–voltage characteristic for fuse saving in distribution networks with DG," *IET generation, transmission & distribution,* vol. 11, no. 1, pp. 272-279, 2017.

[67] S. Jamali and H. Borhani-Bahabadi, "Non-communication protection method for meshed and radial distribution networks with synchronous-based DG," *International Journal of Electrical Power and Energy Systems,* vol. 93, pp. 468-478, 2017, doi: 10.1016/j.ijepes.2017.06.019.

[68] Z. Zhang, P. Crossley, and L. Li, "A positive-sequence-fault-component-based improved reverse power protection for spot network with PV," *Electric Power Systems Research,* vol. 149, pp. 102-110, 2017, doi: 10.1016/j.epsr.2017.04.022.

[69] A. Agrawal, M. Singh, and M. V. Tejeswini, "Voltage current based time inverse relay coordination for PV feed distribution systems," 2016, no. Conference Proceedings: IEEE, pp. 1-6, doi: 10.1109/NPSC.2016.7858866.

[70] M. V. Tejeswini and B. C. Sujatha, "Optimal protection coordination of voltage-current time based inverse relay for PV based distribution system," 2017, no. Conference Proceedings: IEEE, pp. 1-7, doi: 10.1109/ICECCT.2017.8118006.

[71] H. Kılıçkıran, H. Akdemir, İ. Şengör, B. Kekezoğlu, and N. Paterakis, "A Non-Standard Characteristic Based Protection Scheme for Distribution Networks," *Energies,* vol. 11, no. 5, p. 1241, 2018, doi: 10.3390/en11051241.

[72] E. Purwar, D. Vishwakarma, and S. Singh, "A Novel Constraints Reduction-Based Optimal Relay Coordination Method Considering Variable Operational Status of Distribution System With DGs," *IEEE Transactions on Smart Grid,* vol. 10, no. 1, pp. 889-898, 2017.

[73] Y. Damchi, M. Dolatabadi, H. R. Mashhadi, and J. Sadeh, "MILP approach for optimal coordination of directional overcurrent relays in interconnected power systems," *Electric Power Systems Research,* vol. 158, pp. 267-274, 2018, doi: 10.1016/j.epsr.2018.01.015.

[74] M. Singh, V. Telukunta, and S. Srivani, "Enhanced real time coordination of distance and user defined over current relays," *International Journal of Electrical Power & Energy Systems,* vol. 98, pp. 430-441, 2018.

[75] T. S. Aghdam, H. K. Karegar, and H. H. Zeineldin, "Transient stability constrained protection coordination for distribution systems with DG," *IEEE Transactions on Smart Grid,* vol. 9, no. 6, pp. 5733-5741, 2017.

[76] H. M. Sharaf, H. Zeineldin, D. K. Ibrahim, and E. E. D. A. El Zahab, "Protection coordination of directional overcurrent relays considering fault current direction," in *IEEE PES Innovative Smart Grid Technologies, Europe,* 2014: IEEE, pp. 1-5.

[77] C. A. C. Salazar, A. C. Enríquez, and S. E. Schaeffer, "Directional overcurrent relay coordination considering non-standardized time curves," *Electric Power Systems Research,* vol. 122, pp. 42-49, 2015.

[78] A. Yazdaninejadi, S. Golshannavaz, D. Nazarpour, S. Teimourzadeh, and F. Aminifar, "Dual-setting directional overcurrent relays for protecting automated distribution networks," *IEEE Transactions on Industrial Informatics,* vol. 15, no. 2, pp. 730-740, 2018.

[79] K. A. Saleh, M. S. El Moursi, and H. H. Zeineldin, "A new protection scheme considering fault ride through requirements for transmission level interconnected wind parks," *IEEE Transactions on Industrial Informatics,* vol. 11, no. 6, pp. 1324-1333, 2015.

[80] J. Shah, N. Khristi, V. Rajput, and K. Pandya, "A comparative study based on objective functions for optimum coordination of overcurrent relays," in *2017 7th International Conference on Power Systems (ICPS)*, 2017: IEEE, pp. 7-12.

[81] J. Ehrenberger and J. Švec, "Directional overcurrent relays coordination problems in distributed generation systems," *Energies,* vol. 10, no. 10, p. 1452, 2017.

[82] S. M. Saad, N. El-Naily, and F. A. Mohamed, "A new constraint considering maximum PSM of industrial over-current relays to enhance the performance of the optimization techniques for microgrid protection schemes," *Sustainable Cities and Society,* vol. 44, pp. 445-457, 2019.

[83] M. Dewadasa, A. Ghosh, and G. Ledwich, "Protection of distributed generation connected networks with coordination of overcurrent relays," 2011, no. Conference Proceedings: IEEE, pp. 924-929, doi: 10.1109/IECON.2011.6119434.

[84] H. H. Zeineldin, H. M. Sharaf, D. K. Ibrahim, and E. E.-D. Abou El-Zahab, "Optimal Protection Coordination for Meshed Distribution Systems With DG Using Dual Setting Directional Over-Current Relays," *IEEE Transactions on Smart Grid,* vol. 6, no. 1, pp. 115-123, 2015, doi: 10.1109/TSG.2014.2357813.

[85] H. M. Sharaf, H. H. Zeineldin, and E. El-Saadany, "Protection Coordination for Microgrids With Grid-Connected and Islanded Capabilities Using Communication Assisted Dual Setting Directional Overcurrent Relays," *IEEE Transactions on Smart Grid,* vol. 9, no. 1, pp. 143-151, 2018, doi: 10.1109/TSG.2016.2546961.

[86] A. Arab, A. Khodaei, Z. Han, and S. K. Khator, "Proactive Recovery of Electric Power Assets for Resiliency Enhancement," *IEEE Access,* vol. 3, pp. 99-109, 2015, doi: 10.1109/ACCESS.2015.2404215.

[87] A. Yazdaninejadi, S. Golshannavaz, D. Nazarpour, S. Teimourzadeh, and F. Aminifar, "Dual-Setting Directional Overcurrent Relays for Protecting Automated Distribution Networks," *IEEE Transactions on Industrial Informatics,* vol. 15, no. 2, pp. 730-740, 2019, doi: 10.1109/TII.2018.2821175.