Optimal Coordination of Directional Overcurrent Relays Considering Transient States of Fault Current in the Presence of Renewable and Non-Renewable Distributed Generators: A Review

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Abstract- Renewable sources of energy (RSE) are intermittent and have a dynamic nature which export these dynamics to the short circuit (SC) current resulting in the transient states of SC current. So that, considering only the steady-state SC current during the coordination study of directional overcurrent relays (DOCRs) may make the protection system to be in risk. Actually, the nature of the transient states depends on the type of distributed generations (DGs); as in case of synchronous based DGs, the transient states will last for a considerable time that would affect the performance of overcurrent relays. While in case of inverter-based DGs, the rapid transient response of the inverter control system makes the behavior of its fault current to be characterized by quasi steady-state fault current. Hence, the transient states of fault current should be considered during the coordination study of DOCRs in networks with DGs. Moreover, connecting renewable and non-renewable DGs to the distributed networks leads to bidirectional power flow and fault level change which increase the complexity of the coordination problem. Many review papers in the field of DOCRs coordination dependent on the steady-state fault current were presented, which is the motivation behind this work to fill this research gap by introducing a review paper for optimal coordination of DOCRs considering the transient states of fault current with the exist of DGs. Moreover, comparing the pre-proposed techniques in this field of research and outlining the advantages and the dis-advantages of them. Furthermore, discussing transient coordination based references research directions.

Keywords- Renewable energy, overcurrent relays coordination, transient fault, dynamic model of over current relays, optimization methods and review.

1. Introduction

Meshed and multi-source power systems due to the presences of renewable sources of energy (RSE) and synchronous based distributed generations (DGs) in electric power networks require directional overcurrent relays (DOCRs) for effective and economic protection scheme. Actually, two main parameters control the operation time of overcurrent relays (OC) relays; time multiplier setting (TMS) and pickup current (I_p). The values of TMS and I_p of the relays shall be properly calculated through the protection coordination process, such that the primary relay protection must respond to clear any fault in its region as fast as possible. The operating time of any relay must be healthy coordinated with the adjacent relays which add to the complexity of coordination problem [1], [2] and [3]. Moreover, RSE and synchronous based DGs connection of to the distribution network added further problems to the coordination process due to the bidirectional power flow and short circuit (SC) current levels change, which in turn increase the coordination problem complexity [4], [5], [6] and [7]. DG effects on OC relays coordination depend on type, location and size of DGs [8] and [9].

1.1 Background and motivations

Many references such as [1], [10], [11], [12], [13], [14], [15], [16] and [17] have presented reviews for the techniques of coordination of DOCRs based on steady-state fault currents. However, there is a shortage in review papers which present a similar comprehensive view while considering the transient states of short circuit. So that, this paper aims to fill this gap of research by introducing a review study for optimal coordination of DOCRs in the existence of transient states of fault current to find out the most effective optimization technique for practical implementation, that is because the fault current in actual networks has a transient nature response for a considerable period of time, which could not be ignored, before getting settled at a steady state value. Table 1 shows the targets of review papers in the field of DOCRs coordination.

Table 1 Review papers target

REVIEW references	Optimal coordination of DOCRs considering	
	Steady-state fault current	Transient fault current
[1], [10], [11], [12], [13], [14], [15], [16] and [17]	√	X
Proposed review research	X	√

1.2 Literature review

This literature review is arranged as follow; it will briefly explore the recent references related to OC relays coordination in general then explore the effect of renewable energy sources transient, the effect sources transient stability and the effect of network configuration change on DOCRs coordination, after that the references of transient based coordination of DOCRs will be discussed.

Distribution networks with high level of penetration of renewable and non-renewable DGs have different types of protective devices, which make the protection coordination among these devices more difficult [18], [19] and [20], so many papers are seeking to solve this problem with different optimization techniques. In [21], the authors present an adaptive protection technique independent on communication links to resolve the effect of DGs bidirectional power flow on OC relays coordination. A novel optimization method depending on gorilla troops optimizer (GTO) is presented in [22] and [23] for automated settings and optimal coordination of OC relays. In [24], different optimization techniques like (Particle Swarm Optimizer (PSO), Genetic Algorithm (GA), Water Cycle Approach) are presented to solve DOCRs and impedance relays coordination problem in the presence of DGs. In [25], a new coordination technique based on a two-level user-defined characteristics is presented for DOCRs optimal coordination, as each relay will have one user-defined characteristic when it operates as a primary and another characteristic when operating as a backup. In [26], an optimization strategy based on user-defined characteristics of OC relays in microgrids with inserting fault current limiter (FCL) is presented for optimally selecting the relay parameters in both islanded and grid-connected modes of operation. An optimization technique based on the integration of GA and modified firefly algorithm to coordinate DOCRs by optimally selecting both TMS and I_p [27]. In this study, the firefly is updated to obtain global solution then GA is used to solve the optimization problem. In [28], coordination of DOCRs is done with considering the occurrence probability of different system configurations. The optimization aims to find the optimal bundle of settings for each sub-group topology. In [29], a novel optimization technique based on hybridization of GA and sequential quadratic programming (SQP) is introduced for coordinating DOCRs in radial and non-radial distribution networks. Actually, all of the above mentioned references in addition to the following references [30], [31], [32], [33]and [34] are considering only the steady-state value of SC current during coordination.

Renewable energy integration in power system networks is continuously upgrading due to its technical advancement, as well as it is a low-cost and clean energy [35] and [36]. At the end of 2018, the wind power share was about 4.8% of worldwide electricity, which expected to increase to 19% at the end of 2028, thereby avoiding more than three billion tons of CO2 per year [37]. RSE provides many benefits to the distribution systems including enhancement of power quality and reliability, emission reduction, transmission loss reduction, reducing network independabilitly and voltage regulation [38] and [39]. In order to obtain the optimum benefits mentioned above, it is required to find the optimum operating point of renewable energy sources like wind turbine generators (WTG) and photo-voltaic (PV). So that, references [40] and [41] are presenting comprehensive comparative studies for the control techniques used with RSE to get the most benefits from its operation. On the other hand, the integration of renewable DG sources has many effecs on the protection of power system in normal and abnormal operating conditions due to bidirectional power flow and SC current levels change which may cause mal-opearation to the protective system [35], [38], [42], [43], [44], [45], [46], [47] and [48]. Furthermore, RSE such as WTG and PV have an intermittent and unexpected nature, which may disconnnected from the network many times a day, which may magnify the pre-mentioned complications [49] and [50]. Thus, if the relays have a static nature and don't update there settings with the network dynamic performance, this would leads to miscoordinationand blind operation of the existed protection system [44]. So that, the conventional protectection coordination based on static relays will not be vailed in the presences of renewable based DGs and a new design of a protection system is an imminent necessity in ordert to accomodate different operating conditions and transient status of power systems, as pressented in [51] and [52] which suggest using a developed smart OC relays with central processor in networks with highly penetrated renewable DGs to improve the system stability and protection. Reference [53] presents an improved protection method to coordinate the protection of wind farms based on PMSG (permanent magnet synchronous generator) with networks based on the LVRT (low voltage ride through) capability of wind farms.

In most protection coordination references, the transient stability of DGs is assumed to be maintained during fault clearing times. Therefore, the protective devices are coordinated only based on coordination time interval (CTI). However, for an efficient protection scheme, the transient stability of synchronous DGs should be considered during coordination. Therefore, critical clearing time (CCT) as a transient stability index should be considered in coordination problem in addition to the CTI [54] and [55], as the transient instability of power systems happens if the clearing time of the power system disturbances, like SC, transmission line (TL) interruptions and generator losses, does not respect the CCT [56] and [57]. When a fault happens, it is recommended by IEEE Standard 1547 to disconnected all DGs as fast as possible from the network to prevent catastrophic damages [58]. However, the DGs disconnection cancels all their advantages. Besides, their re-synchronization after fault clearing is a challenging issue. So that, some efforts have been done to avoid DGs disconnection after fault occurrence. For example, [59] suggests connecting a FCL in series with induction type DG to remain the stability of generators during fault, while in [56], a two characteristic curves (main and auxiliary) over-current relay had been proposed in which the main characteristic curve replaces the auxiliary one in high levels of fault current situations. Moreover, references [60], [61] and [62] present protection schemes based on DOCRs- due to their high sensitivity and fast response- to prevent the propagation of fault, so maintain power system stability. Furthermore, [63] recommends to consider the requirement of fault ride through (FRT) of doubly-fed induction generator (DFIG) in protection coordination scheme, while in [64], a technique based on communication among DOCRs is presented which enhanced the protection system speed by 49.57% and no stability violation happened.

This paragraph will show briefly how previous references deal with DOCRs coordination in the presence of transient fault current. In [8], a method based on the dynamic model of OC relays is presented to take-over the transient behaviour of synchronous based DGs and FCLs. Due to the non-linear dynamic equation used, the coordination problem is solved by GA as a meta-heuristic technique to calculate TMS of relays. In [65], an integration of linear programing (LP) and GA is used for optimal coordination of DOCRs by optimally selecting TMS and I_p. In [66], the authors present an optimization method based on adapted PSO technique in order to optimally select TSM, I_p and curve type- selected from the standards IEC types shown in Table 2- for each relay in the system. In [67], the authors present an optimization method based on GA for optimal coordination of non-directional OC relays, taking into account the transient fault current contributed from induction motor (IM) during SC states in the industrial power networks. The optimization method presented in this reference is based on the dynamic model of OC relays. In [68], an optimization method based on the dynamic model of OC relays is presented to incorporate the momentary SC of two types of WTGs; synchronous based and doubly-fed inverter interfaced DG (IIDG). In [69], an optimization method for coordinating DOCRs based on LP and the dynamic model of OC relays is presented. The presented solution in this reference intended to consider the topology change effect on the SC current level due to the operation of the relay on the other side of TL. The same concept of optimization in [69] is discussed also in [70] depending on teaching learned- based optimization (TLBO) technique and in [71] based on biogeography-based optimization algorithm. In [72], a coordination algorithm based on the dynamic nature of OC relays is presented which only optimizing TMS while I_p is not optimized.

Table 2 Standard relay characteristic based on IEC 60255

Relay Characteristic	IEC 60255 Characteristics curves constants	
	A	β
Standard Inverse (SI)	0.14	0.02
Very Inverse (VI)	13.5	1
Extremely Inverse (EI)	80	2

The main contribution of this review paper can be highlighted as in the following points:

- Up to the authors' knowledge, no researchers investigated a review study in the field of DOCRs coordination with considering transient states of fault current in reported studies before. So that, this work aims to fill this research gap by introducing this review study.
- This work presents comparisons among DOCRs transient based coordination references, showing the advantages and drawbacks of each one. So that, this work can be considered as a guide for the next researchers in this field.
- This review study presents a general algorithm for the common solution steps followed in the previous related references, which can be more helpful for future works in this field of research.
- This work collects the optimization techniques frequently-used in previous DOCRs transient based coordination works. Moreover, showing the main features, advantages and dis-advantages of each optimization technique from transient coordination point of view, which add value to this presented work.

The organization of the upcoming sections will be as follows. In Section 2, the DOCRs coordination problem in the presence of transient fault is described. In Section 3, the optimization techniques presented in previous works, which consider the transient fault current in the coordination problem, are investigated considering the advantages and the drawbacks of these techniques. Finally, Section 4 presents a conclusion for the presented work in this review paper.

2. Problem Formulation

2.1 Problem definition

In this section, the problems of not taking into account the transient states of SC current during coordination study is shown. In [66], a study is provided to show if there is an error in relays operating times calculated based on fixed steady-state fault value compared to operating times calculated based on actual dynamic signals of fault current. The authors in this reference concluded that for a sample network, presented in this reference, if the operating time of an OC relay is 0.1 calculated based on transient fault current, the relay will have an operating time of 0.13 s calculated based on fixed SC, with an error of 13% for the relay very inverse (VI) characteristic which can lead to miscoordination among protective devices in the system.

Another phenomenon of coordination problems is appeared due to the spread of IMs in different industrial networks. When a SC occurs at the IM terminals or in the power network, the tapered flux in the stator windings is discharged in the form of a transient fault current wave which contributes a transient component to the SC fault. So that, the conventional coordination of OC relays based on fixed fault value will be disturbed. The authors in [67] discuss the effect of IM contribution during SC on non-directional OC relays coordination. Fig. 1 clarifies that the IMs contribute a transient component to the SC, therefor the conventional relay operating time equation (1) will not be valid in this case.

$$t = TMS\ x\ \frac{\alpha}{(\frac{I}{I_p})^{\beta}-1} \quad (1)$$

Where I is the fixed SC and (α and β) are relay constant coefficients.

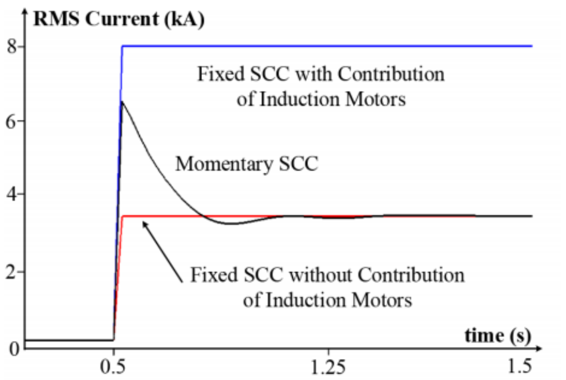

Fig. 1 Momentary SC and (fixed SC with and without IM contribution) [67]

The authors in [67] presents a formula to calculate the error in relays operating time calculated based on fixed fault current compared to real operating time based on momentary SC as shown in (2).

$$time\ error\ \% = \frac{t_{calculated} - t_{real}}{t_{real}}\ x\ 10 \quad (2)$$

where $t_{calculated}$ is the relay operating time using fixed steady-state fault and t_{real} is the real operating time measured by relay based on real momentary fault based on the dynamic model of OC relays presented in IEEE standard C37.112 [73]. From Fig. 1, the following relations are cleared

$$\text{Fixed SC without IMs contribution} < momnetary\ SC < \text{Fixed SC with IMs contribution}$$

$$\text{relay calaclated time(without)} > \text{relay real time} < \text{relay calaclated time(with)}$$

So that, the time error using fixed SC without IM contribution (conventional method 1) will be positive, while the time error using fixed SC with IM contribution (conventional method 2) will be negative. This time error may cause miscoordination between relays in any conventional method. The CTI for both cases is as shown in Fig. 2.

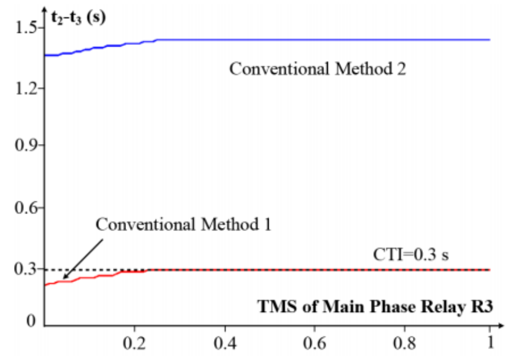

Fig. 2 Calculated time error percentage compared to real operating time [67]

In conventional method 1, the time interval between primary and backup relays will be lower than CTI. On the other hand, in conventional method 2, the time interval between primary and backup relays will be large compared to CTI [67].

Topology change problems, as mentioned in [69], lead to SC level change so faster or slower operation of relays which finally lead to miscoordination.

From the above mentioned problems it is clear that the transient fault current must be considered when calculating the operating time of DOCRs in real networks which require the usage of OC relays dynamic model.

2.2 Overcurrent relays dynamic model

According to IEEE standard C37.112 [73], the dynamic model for inverse-time OC relays is presented as following equations

$$\frac{1}{TMS}\int_{t_0}^{t_x}\left(\frac{1}{F_2(I)} - \frac{1}{F_1(I)}\right) = 1 \quad (3)$$

Where t_0 is the time at which the relay starts to see the SC current and t_x is the operating time of the relay. While F_2 and F_1 are the trip and reset characteristics of the relay, respectively, as shown in (4) and (5).

$$f_2(I_{sc}) = \frac{\alpha}{((\frac{I_{sc}}{I_P})^{\beta}-1)}, \quad \text{where } (\frac{I_{sc}}{I_P}) > 1 \quad (4)$$

$$f_1(I_{sc}) = \frac{t_r}{(1-(\frac{I_{sc}}{I_P})^2)}, \quad \text{where } 0 < \left(\frac{I_{sc}}{I_P}\right) < 1 \quad (5)$$

$f_2(I_{sc})$ is activated when $I_{SC} > I_p$ whereas, $f_1(I_{sc})$ is activated when $I_{sc} < I_p$. I_{SC} is the momentary SC current so it contains the transient states of SC currents. If the value of integration in (3) reaches 1, the relay will send a trip signal, so equation (3) can be called ROS.

3 Optimization Techniques

Actually, DOCRs coordination problem is a highly constrained nonlinear problem, which is solved with different optimization techniques in order to obtain optimal relays settings and minimum operating times or DOCRs. The common optimization techniques used to solve DOCRs coordination problem in the presence of transient states of fault current are as shown in Fig. 3. While the general process flow for the solution steps of optimization techniques used to solve DOCRs transient based coordination problem can be clarified as in Fig. 4. The main features, advantages and dis-advantages of the common optimization techniques used to solve the DCORs coordination problem in the exist of transient states of fault current can be summarized as shown in Table 3.

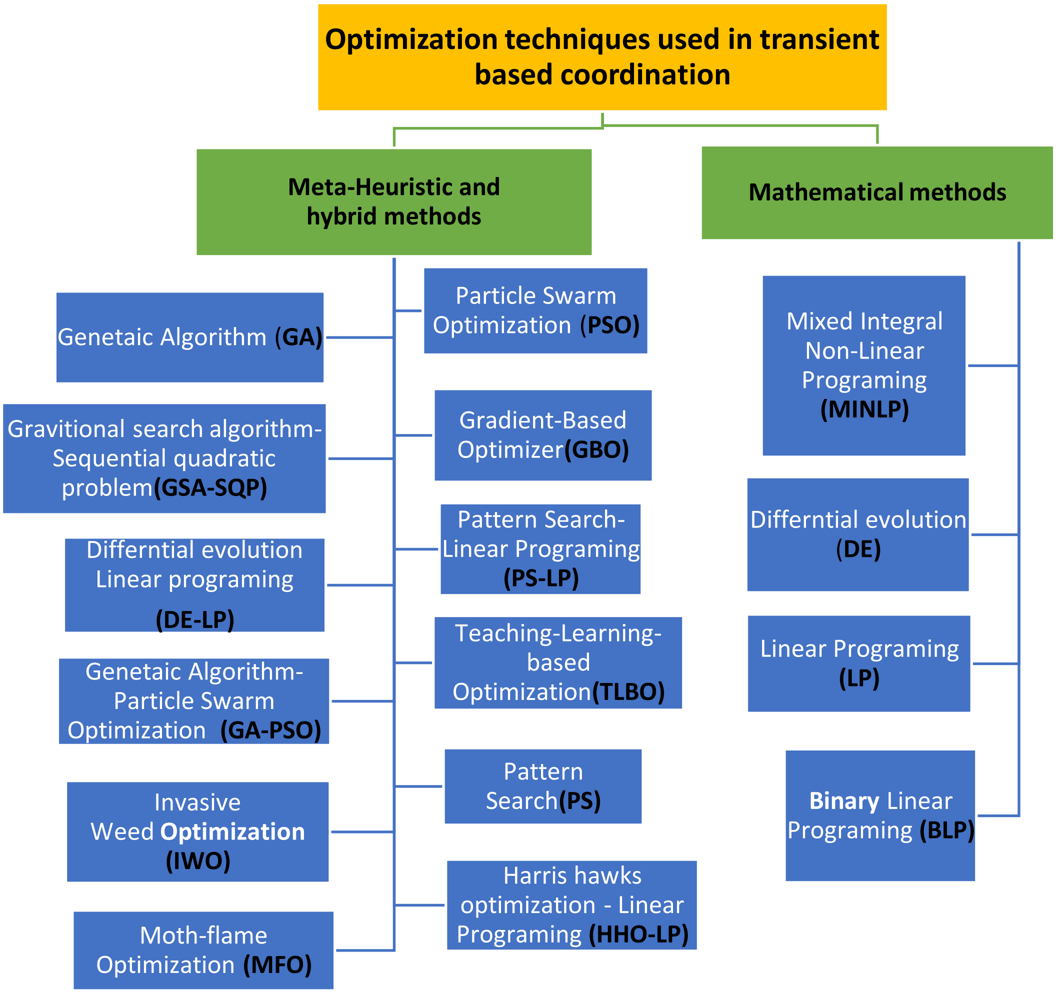

Fig. 3. Optimization techniques used in transient based coordination problems

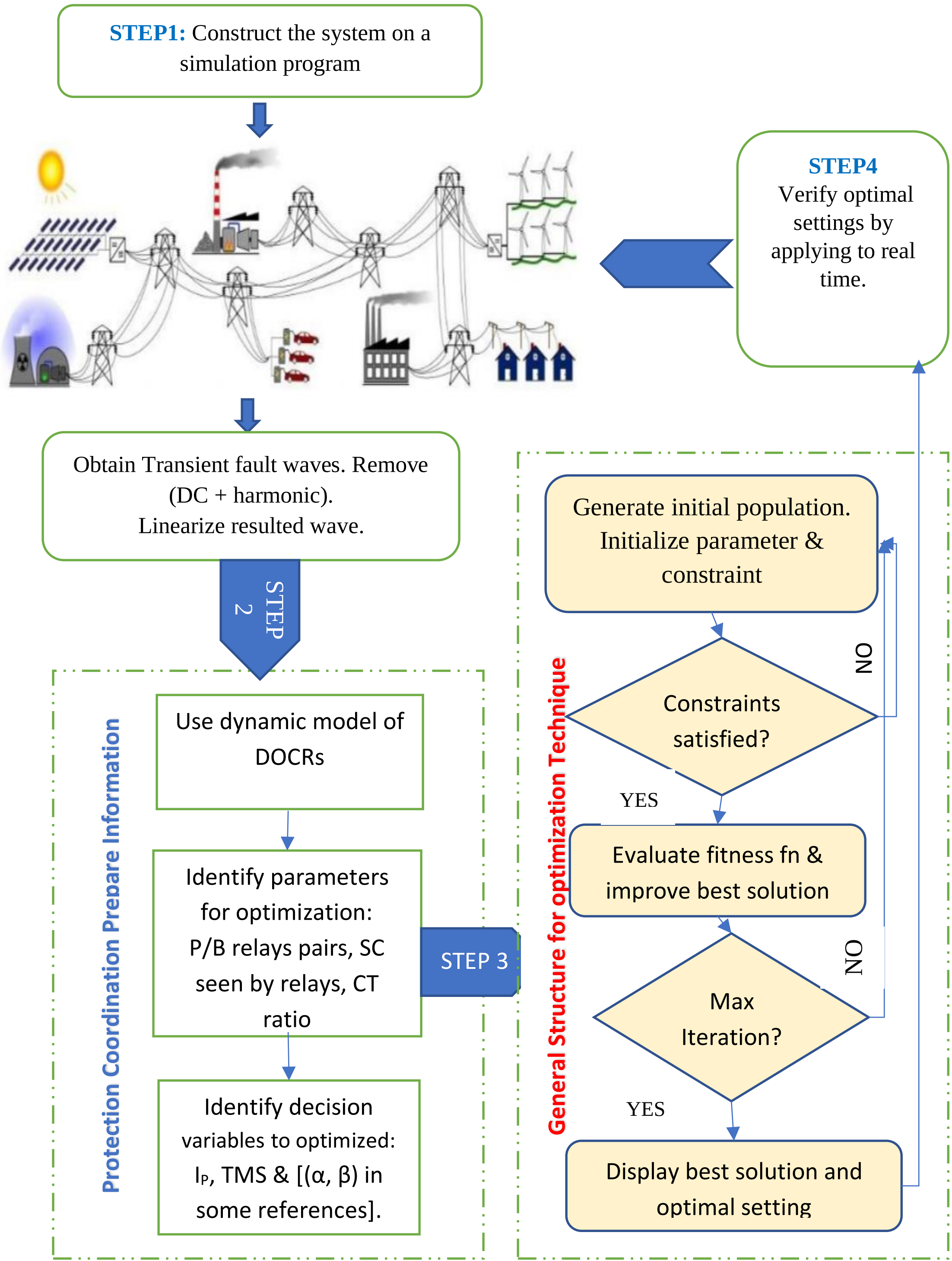

Fig.4 General process flow of optimization techniques used in transient based coordination

Table 3 Main optimization techniques used in transient based coordination of DOCRs

Main optimization techniques used in transient based coordination of DOCRs				
Tech. Type	Tech. Name	Main feature	Advantage	Disadvantage
Meta-Heuristic & Hybrid Techniques	Particle Swarm Optimization (PSO) [3],[66], [74]	obtains the best solution from particles interaction	Less parameters to tune and easy constraints	Early converges so low quality solution
	Genetaic Algorithm (GA) [8], [67] [74],[75],[76]	Modifying (OF) to handle miscoordination by adding new terms	Accurate, flexible and effective	Long computation and calculation time
	GA-PSO [45], [77]	Fasct and accelarate optimization process	High reliable and accurate solution mehtod	Its results need to be validated under network configuaration change
	Gravitional search algorithm-Sequential quadratic problem (GSA-SQP) [37]	Best agent obtained by GSA is used as initoilal value for SQP	Adding SQP to GSA to overcome each method separate drawback	GSA may converge to points whivh not optimum. SQP is a single point search technique, it may be trapped to a local solution
	Differntial evolution Linear programing (DE-LP) [78]	DE is the main optimizer & LP is the sub-problem optimizer	It repeats the algorithm till convrge to optimal solution	LP add large penality to the objective fn if no solution is obtained
	Pattern Search-Linear Programing (PS-LP) [79]	PS explores repeated string of patterns as a global solution and LP identify the best solution	Recognize the patterns quickly	Reqiure large data base entery to enhance accuracy
Mathematical Methods	DE	Effiecient in solving optimization problems based on natural selection of agents	Exploring the search space fist globally and then locally. Less execution time	highly dependent on the control parameters which are not easy to fine tuning
	LP [69], [77] [80], [81], [82]	Simplifying the non-linear objective function by converting it to linear one	Significantly reducing number of constraints	Difficult to solve large-scale optimization problem and low sensitivity. Optimize only one variable.
	Mixed Integral Non-Linear Programing (MINLP) [83]	Two-stage anlytical optimizer	Optimize both discrete and continuous variables. Include non-linear equation	Iteration process consume more time

It can be observed from Fig. 3 and Table 3 that the research directions in the field of DOCRs coordination with considering transient states of fault current are depend only on the intelligence based techniques which are classified into two main categories (meta-heuristic and mathematical methods). While the conventional based methods (trial and error, graph theory and curve fittings) are not used in any transient based reference to solve the protection coordination issues. The number of references related to each category of intelligence techniques is as shown in Fig. 5. Moreover, the number of references per year related to transient coordination of DOCRs is as shown in Fig. 6.

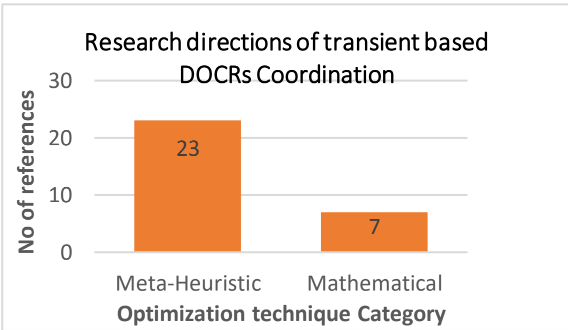

Fig.5 Research direction of DOCRs coordination considering transient

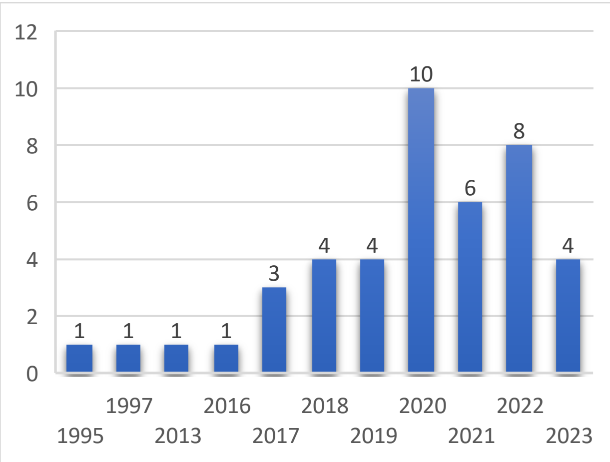

Fig.6 Number of references per year related to DOCRs coordination considering transient

From Table 3 and Fig.5, it can be concluded that the meta-heuristic techniques have a superiority over mathematical approaches in the field of transient based coordination of DOCRs based on the following two points:

- The number of researches based on meta-heuristic techniques are much greater than researches based on mathematical approaches, as shown in Fig.5, which reflect the researchers trust in meta-heuristic techniques.
- The solution obtained from meta-heuristic techniques are more accurate, as the meta-heuristic techniques are added to mathematical approaches to enhance the quality of the obtained optimization settings and to overcome the drawbacks of using only a mathematical model in coordination, as shown following:
  - In [16], a detailed study which proof the superiority of Particle Swarm Optimization (PSO) as a meta-heuristic technique over the Non-linear programming (NLP) as a mathematical technique in the field of relay coordination is present.
  - In [29], a hybrid Genetic Algorithm- Sequential Quadrating Problem (GA-SQP) to enhance the response of (SQP) as a mathematical algorithm.
  - Reference [35] present the using Harris Hawks Optimization - Linear Programing (HHO-LP) to represent the dynamics of wind farms in the adaptive protection schemes.
  - Reference [65] using a hybrid Genetic Algorithm-Linear Programing (GA-LP) to overcome (LP) miscoordination states, and to optimally select (Ip and TMS) instead of optimizing TMS only when using LP alone.
  - In [79], a hybrid Pattern Search- Linear Programing (PS-LP) to enhance adaptive relay settings in the presence of wind turbine units is used.

3.1 Implementation of optimization techniques

In [8], a technique based on OC relays dynamic model and the transient response of FCLs and DGs is presented for DOCRs coordination, GA is used in this reference as a solver for the optimization problem. The general solution steps of this reference are: dividing transient fault currents of main and backup relays into samples, removing harmonic and DC component from the SC wave. The filtered current for each P/B relay pair is applied to (6) to determine the relay operating status, in which $F_2(I_n)$ and $F_1(I_n)$ can be determined as the same as (4) and (5) and P is the number of levels or samples.

$$\sum_{n=1}^{P}\left(\frac{1}{F_2\,(I_n)} - \frac{1}{F_1\,(I_n)}\right)\,\Delta t \qquad (6)$$

The OF presented of this reference [8] is defined as shown in (7)

$$OF = \alpha_1\,\sum(t_i)^2 + \alpha_2\,\sum(\Delta t_{mb} - \beta_2(\Delta t_{mb} - |\Delta t_{mb}|))^2 \quad (7)$$

Where, $\Delta t_{mbk} = t_{bk} - t_{mk} - CTI$ (8)

In (7), the first term is the sum of OC relays operating times and the second term is the coordination constraint while α_1, α_2, β_2 are the weighting factors. Δt_{mbk} is the discrimination time interval between backup and main relays as shown in (8). CTI is taken to be 0.2–0.4s. Although, the method presented in [8] can achieve coordination between relays under transient conditions, it needs large time to run. Moreover, this method only calculates TMS of relay through optimization while I_p current setting cannot be selected optimally through the optimization algorithm.

In [65], a method depending on the dynamic model, mentioned in section 2.2, is presented for optimal coordination of DOCRs with the consideration of transient fault current using a combined (LP-GA) optimization technique to optimally select both I_p and TMS. In this reference, the proposed technique is firstly presented as a two-level linearization approach for simplicity and best understanding the suggested idea then as a multi-level linearization approach for more accurate solution. The common solution steps are; the transient SC current after removing the DC component and harmonics is linearized and sampled into multiple unequal levels, and the average current value of each level is calculated as shown in Fig. 7. Based on the dynamic model equations, the operating time of an OC relay for multi-level SC current is calculated as in (9)

$$\int_{t_0}^{t_1}\frac{dt}{M1\,TMS} + \int_{t_1}^{t_2}\frac{dt}{M2\,TMS} + \cdots + \int_{t_{p-1}}^{t_x}\frac{dt}{Mp\,TMS} = 1 \qquad (9)$$

With some operation on the previous equation, (10) and (11) can be obtained

$$\frac{t_1 - t_0}{M_1} + \frac{t_2 - t_1}{M_2} + \cdots + \frac{t_x - t_{p-1}}{M_P} = TMS \qquad (10)$$

$$t_x = M_p\,TMS + \sum_{i=1}^{p-1} t_i\left(\frac{M_p}{M_{i+1}} - \frac{M_p}{M_i}\right) + t_0\left(\frac{M_p}{M_1}\right) \qquad (11)$$

Where t_0 is the time at which relay sees the fault, P number of levels, t_x is the relay operating time under transient SC. The relay will send a trip signal if the summation of (9) reach 1. Where M_1, M_2 and M for each level are trip times of a relay due to fault current in the equivalent level and calculated based on the trip part of (3), as shown in (12) and (13).

$$M_1 = f_2(I''_f) = \frac{\alpha}{\left(\left(\frac{I''_f}{I_p}\right)^{\beta} - 1\right)} \quad (12)$$

$$M_2 = f_2(I'_f) = \frac{\alpha}{\left(\left(\frac{I'_f}{I_p}\right)^{\beta} - 1\right)} \quad (13)$$

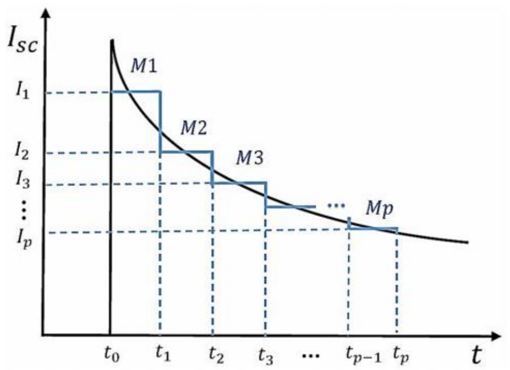

Fig. 7 Levels of the linearized transient fault current [65]

The objective function and constraints of reference [65] are as shown

$$Minimized\ OF = \sum_{i=1}^{N_r} t_i \quad (14)$$

Where i is the number of the relay, t_i is the operating time of relay and N_r is total number of relays The following constraints are applied to the objective function in (14).

$$t_b - t_m \geq CTImin \quad \forall (m\ and\ b) \in \Omega \quad (15)$$

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \quad (16)$$

Where Ω is the primary-backup relays pair and CTI is between 0.2 and 0.4.

From this reference [65], it can be concluded that by increasing the number of levels of transient SC current i.e. decreasing the time interval of samples, the relay operating time error decreased. The advantage of the method in this reference is that it can optimally select I_p and TMS through the coordination algorithm, while its major drawback is the large run time, as it takes 235 min. for IEEE 14 bus test system and 283 min. for IEEE 39 bus test system.

In [66], a method based on OC relays dynamic model is introduced for considering the transient states of fault current during OC relays coordination process, using adapted PSO. The major solution steps are; removing the DC component and harmonics from the transient fault current, dividing the into n-levels based on the selected time period, calculate the RMS values for resulted transient. After the above mentioned common steps, the main solution in this reference is divided into three more steps, first solving for optimally select TMS, second solving to incorporate I_p current in optimization problem and updating it every iteration, while the third step is to select the relay curve type through optimization problem- from the standard curves shown in Table 2.

The objective function in this reference [66] is

$$OF = min \sum_{i=1}^{n_r} [\, t_i\,(I_{max}) + t_i\,(I_{min})] \quad (17)$$

Where n_r is the total number of relays in the system, $t_i(I_{max})$ and $t_i(I_{min})$ are the relay operating times for maximum and minimum SC currents. The problem constraints with transient fault current consideration are as follow:

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \quad (18)$$

$$\Delta t_{mb} = t_b - t_m \geq CTI \quad \forall (m\ and\ b) \in SSP \quad (19)$$

$$t_b = ROS_b^{-1}\,(TMS_b) \quad (20)$$

$$t_m = ROS_m^{-1}\,(TMS_m) \quad (21)$$

$$I_{pi}^{min} \leq I_{pi} \leq I_{Pi}^{max} \quad (22)$$

$$relay\ type\ i\ \in All\ relay's\ charactristics \quad (23)$$

SSP contains all relays pair, t_b and t_m are the backup and main relays operating times, which are computed based on (20) and (21) in order to accommodate transient fault current, in these equations, ROS is calculated as shown in (3). The contribution of the technique presented in [66] is it can incorporate the selection of the I_p and the type of the OC relay curve – selected from IEC standard curves in Table 2- through the optimization technique beside TMS, which enhances relays coordination in the system. By optimally selecting I_p and the curve type in addition to TSM, the value of the objective function (17) is minimized from 14.8099 s to 13.81 s for 19 bus radial system and minimized from 40.02 s to 12.14 s for IEEE 8 bus meshed system using the proposed method – in this reference- based on transient fault current. The main drawback of the presented method in [66] is the large number of constraints which may restrict the optimization technique to find optimal solution easily due to narrow search space.

It worth to be mentioned that, all the solution methods presented in all other OC relays references which consider the transient fault current during coordination problem are depending on the OC relays dynamic model presented in section 2.2 and using in some way one of the optimization methods presented in Fig.3 and Table 3, especially techniques presented in [8] and [65] due to their simplicity compared to ROS technique presented in [66] and [67]. So that, these other papers will be attached as references for further details, which have the following reference number [69], [80], [81], [84] and [85].

4 Conclusion

A timely review for directional over current relays (DOCRs) coordination in the presence of transient states of fault current in distribution networks with renewable sources of energy (RSE) and non-renewable distributed generator (DGs) has been presented in this paper.

This paper concludes that performing the coordination study among protective devices based only on the steady-state fault current can lead to many coordination problems in actual distribution networks due to ignoring the dynamic nature of fault current in real networks. This dynamic nature of fault current can be appeared in actual power networks due to; for example; faster operating time of the relay on one side of the transmission lines with respect to the other side relay; system topology changes and contribution of system equipment like induction motors during SC. This dynamic nature of fault can lead to errors in relays operating times if calculated based on fixed steady-state fault and ignoring the dynamic signals of fault current.

So that, incorporating these transient states of short circuit current in coordination study is a must and hence the OC relays dynamic model must be used. Actually, the dynamic model of OC relays, presented in IEEE standard C37.112, is used in all coordination based transient studies as it provides the ability to calculate the relay operating time based on the momentary SC current by activating the trip part of the relay dynamic model equation.

Moreover, in this paper a comparison between research directions in the field of transient based coordination of DOCRs has been performed, which show a superiority of the meta-heuristic optimization techniques over mathematical based techniques. Actually, this superiority outcome based on the quality and accuracy of the optimization settings obtained and the trust of researchers in meta-heuristic techniques as they using these techniques frequently compared to mathematical-based techniques.

Furthermore, the advantages and drawbacks of the optimization techniques used in transient based coordination have been presented which can be concluded as follow.

The general advantages of mathematical techniques are; they are effective for simple distribution networks and are the corner-stone and the origin of the advanced optimization technique as they are derived from proofed mathematical formulation. While the common drawback in the field of DOCRs coordination is that some of them consider discrete values for pickup current settings which reduce the accuracy of the obtained settings and they could be stuck to local minimum.

The general advantages of meta-heuristic techniques are; multiple point search technique, converge to global minimum, overcome mathematical drawbacks and the great abilities in analyzing and storing numerous data. On the other hand, their common drawback they may take longer time than mathematical techniques.

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