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ORIGINAL PAPER

Hybrid GA-IPM algorithm for optimal protection coordination of directional overcurrent relays with mixed time current characteristic curves

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Abstract

This paper presents an improved directional overcurrent protection scheme using a two-stage hybrid GA-IPM algorithm. The developed approach considers the optimal time-current characteristic (TCC) selection and setting calculations of DOCRs simultaneously to protect meshed power networks. The developed formulation considers the optimal choice of the TCC curve and setting calculation simultaneously. Here, the problem is formulated as a mixed-integer nonlinear programming (MINLP) problem where a curve selection setting called curve-setting (CS) is added to the standard time multiplier-setting (TMS) and plug-setting (PS) of each relay in the DOCRs-based protection scheme. In modern relays, the selection of TCC curves is easily made from the available options. In this work, the IEC-standard curves have been considered to obtain the optimum characteristic curve selection and setting calculations. The formulated MINLP problem has been solved using the newly developed two-stage hybrid GA-IPM algorithm. In the first stage, the genetic algorithm (GA) is used to solve the problem formulated as MINLP. The obtained solution is considered the initial solution for the interior-point method (IPM) in the second state. The GA can solve the MINLP problems effectively, and IPM is superior in solving nonlinear programming problems, hence fine-tuning the results obtained by GA. The suitability and effectiveness of the proposed approach have been demonstrated on the IEEE 14 bus test system. Further, the efficacy of the developed method has been validated on an extensive IEEE 118 bus test system, and results are compared with those available in the literature.

Keywords Time-current characteristic curve · Directional overcurrent relays · Genetic algorithm · Power network · Protection coordination

1 Introduction

Overcurrent principle-based protections have been widely used in medium- and low-voltage power networks since the inception of power transmission [1]. In interconnected power networks, the flow of current is bi-directional, and for proper protection lines/cables of such networks, relays are required from both ends [2]. Additionally, the protective relays' directional feature becomes inherent to properly meet the protection scheme's selectivity requirements. This evolves directional overcurrent relays (DOCRs) that handle protection tasks adequately. However, meeting proper protection coordination among various relays becomes a more complicated task compared to those of radial power networks [3].

Usually, protection coordination is achieved using the setting of relays so that for any fault, the nearest relay should operate sufficiently fast to remove the faulted section by generating a trip command to the associated circuit breaker (CB). If the nearest protective relay fails to clear the fault, all the backup relays related to the nearest relay should generate a trip command to operate their CBs so that the fault gets cleared [4]. The nearest relay to the fault will remove a small section of the network, while the backup relays will remove a larger section of the network unnecessarily [5]. Removing a larger section interrupts many consumers' power supply, reducing reliability. However, the operation of backup relays is needed to mitigate the impact of fault on a far larger network section [6]. Therefore, a strategy is adopted to allow

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the fault to be cleared by the nearest relay to the fault point, called a primary or main relay, by delaying the operation of all the associated backup relays with a minimum time margin [7]. All the relays sense the fault simultaneously because they observe very high current and low voltage depending on their locations to the fault and sources in the network. Hence, a priority needs to be set to allow the primary relay to operate first and backup relays to operate with a minimum delay, called coordination time interval (CTI). This task is achieved using properly selecting relay setting parameters called time-multiplier setting (TMS) and plug-setting (PS) [8]. This issue of maintaining CTI is termed a protection coordination problem.

The operating time of a relay for a given fault current primarily depends on TMS, PS, and TCC curve types. [9]. As per the IEC 60255-151, most of the DOCRs used to follow one among the normal inverse (NI), very inverse (VI), and extremely inverse (EI) TCC curve [10]. All these TCC curves are available in the same relay block, and one among them can be selected at a time for the protection application. These relays can accept any values of TMS and PS parameters in their range [11].

Finding the settings of the relays for properly maintaining CTI among all the primary backup relay pairs of DOCRs considering the requirements mentioned above (reliability, selectivity, speed, and sensitivity) is a challenging task in interconnected networks. Mostly, optimization-based approaches are adopted for solving the protection coordination problem of DOCRs in interconnected power networks [12–19]. These approaches have shown great potential to provide proper protection coordination. However, in these studies, only one fixed type of TCC curve of the relays has been considered.

Additionally, to provide better protection coordination, several other types of characteristic curves have been proposed in the literature [20–30]. These curves are mostly non-conventional and defined by the users [20–27]. The main advantage of these approaches is that the operating time of the relays is not determined by the conventional TCC curve but by the optimally selected one. Usually, the TCC curves are chosen to vary between NI and VI relays. In other words, these TCCs try to explore the possibility of selecting a user-defined curve for each relay so that their characteristics are within the curves of NI and VI. Such a TCC gives relatively reduced operating times of the relays because of employing a compromised TCC curve. However, there are two difficulties with these curves: obtaining optimum settings is very difficult because of associating a minimum of two more variables for each relay. While fixing the settings of the relays for field application, extreme care is to be taken because, for each relay, a minimum of four setting parameters are to be fixed as compared to only two setting parameters in the conventional approach. Even though the settings obtained using such an approach are better than those considering a single TCC, the overall optimization problem becomes very complicated because of the association of more variables.

Some of these conventional curves have multiple curve options [28–30]. In [28], curve selection and setting calculation are proposed together. This work defines different types of curves by four standards, including IEEE and IEC. A total of ten types of standard curves have been considered, of which IEC curves give superior protection coordination. In [29], five types of conventional curves have been considered and tested on a radial distribution network. In [30], seven curves of IEEE and IEC have been considered to obtain optimal relay settings for better protection coordination. With the results of these works, it is clear that most relays require IEC curves.

Communication-assisted protection schemes using DOCRs have recently been proposed for proper protection coordination. A communication-assisted protection scheme is proposed in [31] to protect the radial distribution network with distributed generations. A superior protection scheme utilizing dual DOCRs and communication links is presented in [32] to protect medial voltage microgrids with the grid-connected and islanded-mode operation. The protection coordination issues associated with different fault locations in dual DOCRs-based protection schemes are discussed in [33]. A faster protection scheme has been presented in [34], aiming to break the chains in the corresponding loops by deploying auxiliary DOCRs in an active distribution network using communication links. The proportion coordination problem of DOCRs is proposed to minimize the energy-not-supplied (ENS) instead of the sum of operating times of all the relays in [35] for the networks having DGs. Also, a new protection scheme is proposed in [36], which involves developing a voltage index (VI) and introducing a new characteristic aimed at minimizing ENS for the protection of power networks dominated by inverter-based distributed generations (IBDGs). These schemes provide improved protection coordination and reduced overall operating times of relays. However, the issue with such advanced protection schemes is the need for additional hardware requirements such as nonconvention relays, dual DOCRs, auxiliary DOCRs, and communication links, which take time to apply to the actual system for protection.

From the above discussion, it is clear that the setting calculation is more straightforward in conventional TCC. The setting obtained by a user-defined curve where TCCs lie between NI and VI gives better setting results. Therefore, an attempt has been made to combine both advantages by considering NI, VI and EI curves and setting computation. Here, one additional variable is used in the conventional approach to select proper TCC curves among the curves refined by IEC. Therefore, the possibility of getting better protection coordination and a standard type of curve is obtained, which makes it easy for the field worker to fix the setting of the relays. A preliminary study reported in [37] suggests that considering TCC curve selection and setting the computation of relays can improve the performance of DOCRs-based protection schemes. An improved problem formulation and an effective algorithm must be developed.

In this work, the protection coordination of DOCRs has been reformulated as a mixed-integer nonlinear programming (MINLP) problem where a curve selection setting called curve-setting (CS) is added to the standard setting calculation, i.e., TMS and PS with each relay in the DOCRs-based protection scheme. A new algorithm, GA-IPM, uses the genetic algorithm (GA) and interior-point method (IPM) to solve the formulated MINLP problem of simultaneous curve selection and setting calculation in MATLAB. The developed algorithm is a two-stage hybrid GA-IPM optimization algorithm. The formulated problem is solved in the first stage using the GA to get an intermediate result. The obtained CS values are kept fixed, the remaining PS and TMS values of all the relays are used as the initial solution for IPM in the second stage, and the problem is solved as an NLP problem. The intermediate result gives a sub-optimal solution, whereas the second stage provides the optimum solution for the formulated problem. The proposed protection coordination studies have been investigated on the IEEE 14-bus test system. Additionally, the effectiveness of the proposed scheme is validated in a large IEEE 118-bus test system.

The novelty of the presented work can be summarized as follows:

- Formulation of curve selection and setting calculation of relays as an optimization problem.
- Development of two-stage hybrid GA-IPM algorithm for solving MINLP problems.
- Solution of formulated DOCRs protection coordination problem as a MINLP problem using the newly developed two-stage hybrid GA-IPM algorithm and obtaining superiors and the optimum values of CS, PS and TMS for all DOCRs.
- Investigation of the optimum settings calculation on the standard IEEE 14 bus test system considering all combinations of the IEC curves.
- Performance analysis of the developed two-stage hybrid GA-IPM algorithm and the obtained optimum settings of DOCRs using mixed-time-current characteristics.
- Testing of the developed protection scheme on an extensive IEEE 118 bus test system and comparison of the results available in the literature.

The rest of the paper is organized as follows. The problem statement is discussed in Sect. 2. The adopted solution approach is mentioned in Sect. 3. Results and discussion are presented in Sect. 4. Finally, the presented work is concluded in Sect. 5.

Table 1 Characteristic coefficients of DOCRs

TCC curve	λ	η
Normal inverse (NI)	0.14	0.02
Very inverse (VI)	13.5	1
Extremely inverse (EI)	80.0	2

2 Problem statement

2.1 Protection coordination

The protection coordination status of primary-backup relay pairs of OCRs/DOCRs is analysed based on the CTI between the operating times of the pairs. Mathematically, the CTI of a primary-backup relay pair is defined as follows:

$$\mathrm{CTI} = t_{\mathrm{ob}} - t_{\mathrm{op}} \tag{1}$$

where t_{op} and t_{ob} are the primary and backup relay operating times, respectively, and CTI is the time gap between the operating times of the primary and its backup relay. The operating time of a relay is obtained from its TCC. As per the IEC 60255 [10], the operating time of a relay is expressed as,

$$t_{\mathrm{op}} = \mathrm{TMS} \times \left[\frac{\lambda}{(I_F/\mathrm{PS})^{\eta} - 1} \right] \tag{2}$$

where

- TMS : time-multiplier setting parameter of the relay
- PS : plug-setting parameter of the relay
- I_F : fault current passing through the relay
- λ and η : relay TCC coefficients given in Table 1

The operating time of a primary relay (t_{op}) or backup relay (t_{ob}) can be obtained using the above equation.

The protection coordination status of a primary-backup relay pair is identified as whether coordination holds or is lost depending on the CTI value of the pair [38]. It is expected that the CTI value of a pair must be more than the minimum coordination time (MCT) for proper coordination. The coordination status of a primary backup relay pair is identified as follows:

- CTI $<$ MCT: coordination lost
- CTI $\geq$ MCT: coordination holds

The range of MCT lies between 0.2 and 0.3 sec [39]. This time gap ensures that the primary relay gets adequate time to operate before the backup relay takes control to clear the fault.

It is to be noted that the PS parameters of relays are expressed as multiples of the current transformer (CT) secondary rating. For this, CT's secondary rating needs to be fixed. Also, the fault current which allows relays to operate is the CT secondary side current. Hence, the actual fault current should be appropriately scaled down on the secondary side of the CT. Also, its CT ratio and primary side rating must be properly selected to avoid a CT situation.

2.2 Problem formulation

To simultaneously obtain each relay's relay settings and curve type, the protection coordination problem is reformulated by combining the optimum setting calculated related formulation [14] and curve selection related variable, i.e., CS. Mathematically, this problem can be formulated as follows:

$$\mathrm{OF} = \min\left(w_1 \sum_{k=1}^{m}\left(t_{\mathrm{op},k}^{\mathrm{CS}}\right)^2 + w_2 \sum_{j=1}^{n}\left(t_{\mathrm{ob},j}^{\mathrm{CS}} - \mathrm{MCT}\right)^2\right) \tag{3}$$

Subject to

$$t_{\mathrm{ob},j}^{\mathrm{CS}} - t_{\mathrm{op},i}^{\mathrm{CS}} \geq \mathrm{MCT} \tag{4}$$

$$\mathrm{TMS}_{k,\min} \leq \mathrm{TMS}_k \leq \mathrm{TMS}_{k,\max} \tag{5}$$

$$\mathrm{PS}_{k,\min} \leq \mathrm{PS}_k \leq \mathrm{PS}_{k,\max} \tag{6}$$

$$t_{k,\min} \leq t_{\mathrm{op},k}^{\mathrm{CS}} \leq t_{k,\max} \tag{7}$$

$$1 \leq \mathrm{CS} \leq 3;\ \mathrm{CS} \in \{\mathrm{integer}\} \tag{8}$$

where

- $t_{\mathrm{op},k}^{\mathrm{CS}}$: operating time of primary relay R_k for CS type TCC curve
- $t_{\mathrm{ob},j}^{\mathrm{CS}}$: operating time of backup relay R_j for CS type TCC curve
- TMS_k : TMS of relay R_k
- $\mathrm{TMS}_{k,\min}$: lower limit on TMS of relay R_k
- $\mathrm{TMS}_{k,\max}$: upper limit on TMS of relay R_k
- PS_k : PS of relay R_k
- $\mathrm{PS}_{k,\min}$: lower limit on PS of relay R_k
- $\mathrm{PS}_{k,\max}$: upper limit on PS of relay R_k
- $t_{k,\min}$: lower limit on operating time of relay R_k
- $t_{k,\max}$: upper limit on operating time of relay R_k
- CS_k : type of curve of relay R_k (either NI, VI or EI)
- m : total number of relays present
- n : total number of backup relays

Table 2 Curve type of DOCRs

TCC curve	CS index
Normal inverse (NI)	1
Very inverse (VI)	2
Extremely inverse (EI)	3

- MCT : minimum CTI required for coordination
- w_1 and w_2 : non-negative weighting factors
- OF : objective function

The TCC curve type of the relay is represented using the CS parameter, which is associated with all the relays. Its value may be either 1, 2 or 3, representing NI, VI or EI types of TCC curve of the relay, respectively. In other words, CS is an integer variable where $CS \in \{1, 2, 3\}$. This is supposed to be the third setting parameter of DOCR. The characteristic curve setting, i.e., the CS value of the relay, is defined in Table 2.

Some primary backup relay pairs in which backup relays may have much fewer fault currents passing through them than the primary relay. Such pairs always satisfy the MCT requirement. Such pairs must be removed while solving the above-formulated protection coordination problem because they burden the solver extra. These relay pairs satisfy the following conditions,

$$I_{f\mathrm{back}} < \max(2 \times I_{L\max}, I_{f\min}) \tag{9}$$

where $I_{f\mathrm{back}}$ is the fault current passing through the backup relay of the primary-backup relay pair under consideration; $I_{L\max}$ and $I_{f\min}$ are the maximum load current, and the minimum fault current encountered by the backup relay of the pair.

2.3 Selection of weighting factors

The selection of weighting factors (w_1 and w_2) plays a crucial role in compromising the operating times of primary and backup relays. A higher weighting factor value associated with the primary relay summation term can reduce the operating times of primary relays but not considerably reduce the operating times of backup relays. This results in higher values of CTI between primary-backup relay pairs in the obtained solution. Similarly, a higher weighting factor value associated with the backup relays summation term can significantly reduce the operating times of backup relays and the CTI value between primary backup relay pairs. However, the operating times of primary relays are relatively higher. Therefore, there is a need to select these values carefully so that the operating times of primary and backup relays are adequately reduced, along with each pair's CTI value. The

Table 3 SOTPB for different values of w_1 and w_2

Sl. no	w_1	w_2	SOTPB(s)
1	0	1	87.31
2	0.1	0.9	58.21
3	0.2	0.8	56.09
4	0.3	0.7	54.48
5	0.4	0.6	53.52
6	0.5	0.5	53.17
7	0.6	0.4	52.82
8	0.7	0.3	52.62
9	**0.8**	**0.2**	**52.47**
10	0.9	0.1	52.57
11	1	0	56.60

Bold data indicates the best data of the row/column

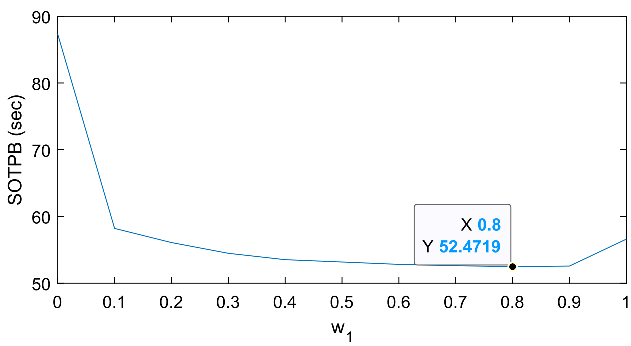

Fig. 1 SOTPB Vs weighting factor w_1

CTI values are supposed to remain close to or slightly more than MCT but not very high. For this, a metric is defined for different values of w_1 and w_2 in terms of the sum of the operating times of primary and backup relays (SOTPB). This can be expressed as follows:

$$\text{SOTPB} = \sum_{k=1}^{m} t_{\text{op},k}^{\text{CS}} + \sum_{j=1}^{n} t_{\text{ob},j}^{\text{CS}} \quad (10)$$

The above equation calculates SOTPB by optimizing the developed problem formulation for different combinations of w_1 and w_2. For this work, standard inverse IDMT characteristics for all the relays have been considered. It is understood that the sum of two weighting factors must equal one to make a good compromise between them. This can be expressed as follows:

$$w_1 + w_2 = 1 \quad (11)$$

From the above equation, it is clear that for any considered value of w_1, w_2 will equal $1 - w_1$. Now, for different values of w_1 and w_2, the SOTPB are given in Table 3 and plotted and shown in Fig. 1. In this figure, only w_1 is shown as w_2 is dependent on w_1 and is known precisely.

From Fig. 1, it is clear that the minimum value $SOTPB$ is 52.4719 s for $w_1 = 0.8$. This indicates that the value of w_2 is 0.2. For different values of w_1 and w_2, the value of SOTPB is given in Table 3. This table shows that for $w_1 = 0.8$ and $w_2 = 0.2$, the value of SOTPB is the least. Therefore, the optimum weighting factor values are in the 9th row of Table 3.

Hence, $w_1 = 0.8$ and $w_2 = 0.2$ have been used in this paper's optimisation work.

2.4 Calculation of CT primary rating and ratio

The CT ratio is mostly selected based on the maximum load current. Its primary rating can be fixed to avoid CT saturation based on the maximum load current and the maximum possible short-circuit current that can flow through it, as suggested in [2]. The primary side rating of the CT required for relay R_i is selected as the next higher standard value of CTP_i, which is calculated as,

$$\text{CTP}_i = \max\left(I_{L\max,i}, \frac{I_{f\max,i}}{20}\right) \quad (12)$$

where $I_{L\max,i}$ is the maximum load current and $I_{f\max,i}$ is the three-phase fault current passing through relay R_i. Now, the ratio of the CT associated with relay R_i is fixed as $\text{CTP}_i : 1$.

2.5 Protection coordination for near-end and far-end faults

The fault current is very high for a near-end fault and low for a far-end fault. The DOCRs coordinate well for far-end faults if the coordination holds for near-end faults. This is because of the inverse TCC of DOCRs. The fault currents passing through primary-backup relay pairs are reduced for far-end faults. This leads to the moving of the operating points of relays towards the left on the TCC curves, which ultimately increases the CTI value of the relay pair. Figure 2 shows that as the fault current reduces (near-end fault), the operating times of both primary and backup relays move towards the left. This increases the time gap between the operating times of primary and backup relays, which causes a relatively higher CTI value ($\text{CTI}_{\text{far-end}}$) as compared to that for near-end fault CTI value ($\text{CTI}_{\text{near-end}}$). Hence, protection coordination is maintained for lower fault current values (far-end faults) if the coordination is maintained for the maximum fault current values (near-end faults).

2.6 Combination of different TCC curves

Three highly used TCC curves of inverse definite minimum time (IDMT) relays exist. The possible combination among these curves may be expressed in a combinatorial form where any one among the three options, any two from the three

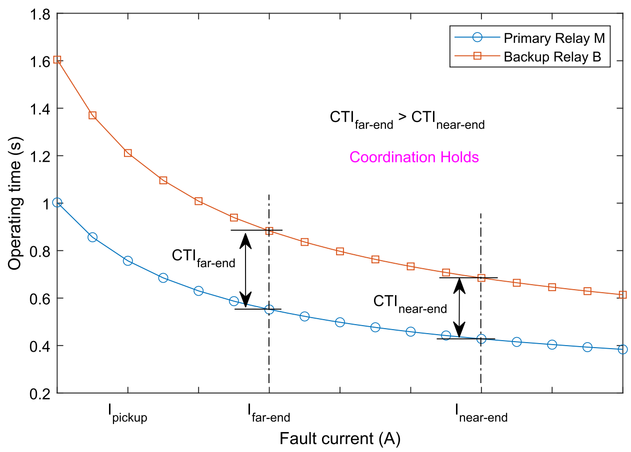

Fig. 2 Protection coordination for the minimum (far-end) and maximum (near-end) fault current values

Table 4 Curve type of DOCRs

Selection	Combination	CS index	TCC curves
Single curve	$^3C_1$	1	NI
		2	VI
		3	EI
Two curves	$^3C_2$	1, 2	NI-VI
		1, 3	NI-EI
		2, 3	VI-EI
All three curves	$^3C_3$	1, 2, 3	NI-VI-EI

options, and all three options can form all possible combinations. Therefore, the total number of combinations among these three relays can be expressed as,

$\text{Total}_{\text{combination}} = {}^3C_1 + {}^3C_2 + {}^3C_3$

Here, the first combinatorial term is associated with selecting any one among the three different types of TCC curves, the second combinatorial term is related to choosing any two TCC curves among the three different types of TCC curves, and the last combinatorial term is associated to selecting all the three different kinds of TCC curves. Table 4 gives all possible TCC curves of DOCRs to be used in the proposed curve selection and setting computation.

From Table 4, it is clear that there is a total of seven possible combinations among different TCC curves of the relay. These combinations are NI, VI, EI, NI-VI, NI-EI, VI-EI, and NI-VI-EI. Now, the task is to provide optimum settings for each combination. Only optimum setting calculations are needed in the first three cases, as the curve selection is already available. On the other hand, optimum curve selection and setting calculations will be made simultaneously in the remaining four cases. Among these four cases, the last case associates all three types of TCC curve options available to each relay along with the setting computation. In the remaining cases, two options are for curve type selection and setting computation for the proper network protection.

3 Developed solution methodology

The standard protection coordination problem is a nonlinear optimization problem where different metaheuristic algorithms have been utilized to solve them to get the proper setting of the relays [12]. Only each relay's TMS and PS parameters are optimized in this formulation. These two setting parameters are treated as continuous variables in numerical relays. In the proposed approach, a third setting parameter, CS, is also associated with selecting the TCC curve for each relay. This CS parameter is an integer in nature and thus makes the problem more complicated. Therefore, each relay's TMS, PS and CS values must be optimized and formulated in the previous section.

The metaheuristic GA has shown great potential to solve complicated MINLP problems. However, the standard GA often gets stuck in sub-optimal solutions while solving complex protection coordination problems [19]. On the other hand, the IPM has shown excellent performance in solving NLP types protection coordination problems, as reported in [40]. The setting calculation for DOCRs obtained by IPM is optimal [14]. However, unlike the GA, IPM cannot solve the MINLP problem directly.

In this paper, a hybrid GA-IPM algorithm has been developed by utilizing the merits of GA for solving the MINLP problem and IPM for solving the NLP problem. The developed algorithm is a two-stage hybrid GA-IPM algorithm discussed in the following subsection.

3.1 Proposed hybrid GA-IPM algorithm

The developed GA-IPM algorithm solves the formulated MINLP problem in two stages. In the first stage, standard GA is applied to solve the problem formulated as a MINLP problem to get the optimal values of CS, PS and TMS, as the obtained solution by GA cannot always be optimal. Therefore, in the second stage, IPM is applied by keeping the integer values of CS obtained by GA the same, and hence, the problem is solved only for getting the optimum PS and TMS variable values. The PS and TMS values obtained by GA are used as the initial solution to IPM to improve further the solution to get their final optimal values. In other words, the optimum characteristic curve selection is made at the first stage by GA, and the optimum settings of the relays are computed in the second stage by IPM. Thus, the optimum values of the three variables associated with each relay, CS, PS and TMS, are obtained using the proposed hybrid GA-IPM algorithm. These are the basics of the developed solution methodology.

3.1.1 Stage-I: GA stage

The GA is a population-based metaheuristic evolutionary optimization algorithm inspired by the fitness of survival in human evolution. This optimization algorithm performs three major steps, selection, crossover and mutation, to get an improved solution at each iteration. The solution vector in this algorithm is known as a chromosome, and many chromosomes form a population. Thus, all the steps are performed on these chromosomes to get the optimal solution. The GA is suitable for solving linear, nonlinear and mixed-integer optimization problems. More details on GA can be found in the literature.

In this stage, the chromosome of the GA is defined by considering integer and continuous variables of the formulated problem. For ease of understanding, three sets of vectors, namely TMS, PS and CS, are used in the proposed formulation for all the relays discussed earlier. Together, these three sets of vectors form the chromosome vector for GA. The chromosome vector of relay settings is expressed as

Chromosome vector = $|\text{TMS}|\text{PS}|\text{CS}$

where

- $\text{TMS} = [\text{TMS}_1, \text{TMS}_2, ..., \text{TMS}_m]$
- $\text{PS} = [\text{PS}_1, \text{PS}_2, ..., \text{PS}_m]$
- $\text{CS} = [\text{CS}_1, \text{CS}_2, ..., \text{CS}_m]$

This chromosome vector represents a set of TMS, PS and CS values of all the relays, which is a potential solution to the problem. Chromosome vectors together form the population matrix of GA. After that, a standard GA solver is used to solve the formulated problem in the MINLP domain to get the intermediate solution. The key steps in this stage are described in Algorithm 1.

The CS, PS, and TMS values obtained after solving through GA are treated as intermediate results and used as the initial solution to the next stage of the IPM-based algorithm.

Algorithm 1 – GA stage

1: Read I_{Lmax}, I_{fmax}, I_{fmin}, $CT\ ratios$, primary-backup relay pairs, I_{fprim}, I_{fback}

2: Set lower and upper bounds on optimization variables CS, PS, and TMS

3: Set CS variable indices as an integer for each chromosome

4: Set iteration count $k = 1$ and maximum iteration Max_k

5: Initialize population using chromosome vectors $[TMS, PS, CS]$ within the bounds for GA

6: Perform *selection* of chromosomes, *crossover* of parents and *mutation* of off-springs to form a new set of chromosomes of GA

7: *Evaluate fitness* and *update population*

8: **if** $k \leq Max_k$ **then**

9: *Goto* step 6

10: **else**

11: *Stop* and *print best chromosome* of GA

12: **end if**

13: Obtain the values of CS, PS and TMS from the best chromosome

3.1.2 State-II: IPM stage

The IPM is an analytical optimization algorithm for solving linear and nonlinear optimization problems. For applying this algorithm, the formulated optimization problem must have twice-continuously differentiable objective functions and constraints in the entire variable domain. The formulated problem relaxed from MINLP to NLP by fixing CS values is a well-defined problem for IPM, and the optimum solution is achievable. The best feature of this algorithm is that it gives unique and optimum solutions in each run [14, 40].

In this stage, the CS values obtained through GA in the first stage are kept fixed, and optimization is performed to obtain improved PS and TMS values of the relays. As the integer variable is no longer there in this approach, the optimization problem is relaxed to the NLP type, where IPM is used to get the optimal values of PS and TMS. The lower and upper bounds on PS and TMS are considered the same as in the GA approach to explore the entire search space. Also, to keep the merits of the intermediate solution, the initial solution required by the IPM is kept the same as obtained by the GA in the previous stage.

Here, the main aim is to get the optimal settings of DOCRs for the characteristic curves obtained in the first stage. Thus, the overall optimization is solved using the two-stage hybrid algorithm for the relays. The key steps used in this final stage are described in Algorithm 2.

Algorithm 2 – IPM stage

1: Re-read I_{Lmax}, I_{fmax}, I_{fmin}, $CT\ ratios$, primary-backup relay pairs, I_{fprim}, I_{fback}

2: , Redefine problem formulation by fixing CS value for each relay as obtained by the first stage

3: Set lower and upper bounds on PS and TMS

4: Set initial solution vector as $[TMS, PS]$ obtained in the first stage by GA

5: Solve the formulated problem by keeping CS values fixed using IPM as an NLP problem for TMS and PS

6: Print the optimum values of PS and TMS obtained by IPM and CS obtained by GA as the final solution.

Finally, the optimum values of CS, PS and TMS associated with each relay are obtained using the two-stage hybrid GA-IPM algorithm.

A flowchart of the developed two-stage hybrid GA-IPM approach is given in Fig. 3. The first four blocks are associ-

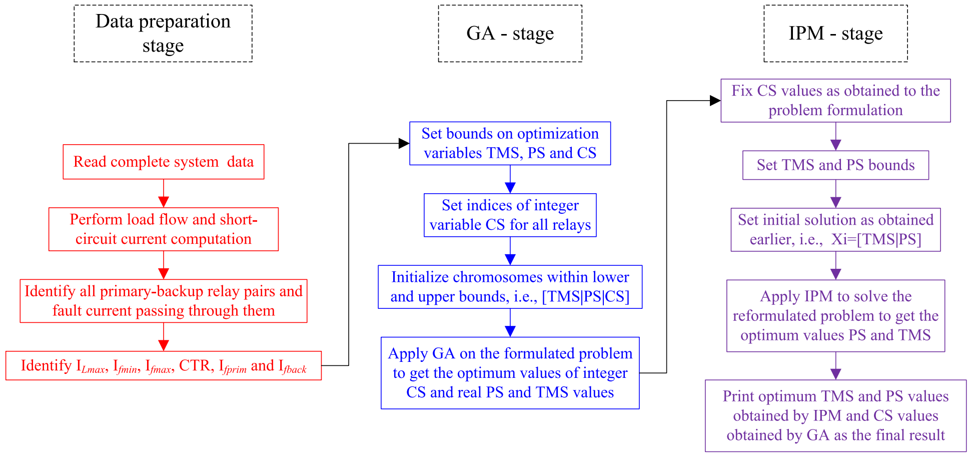

Fig. 3 Steps of two-stage hybrid GA-IPM solution methodology

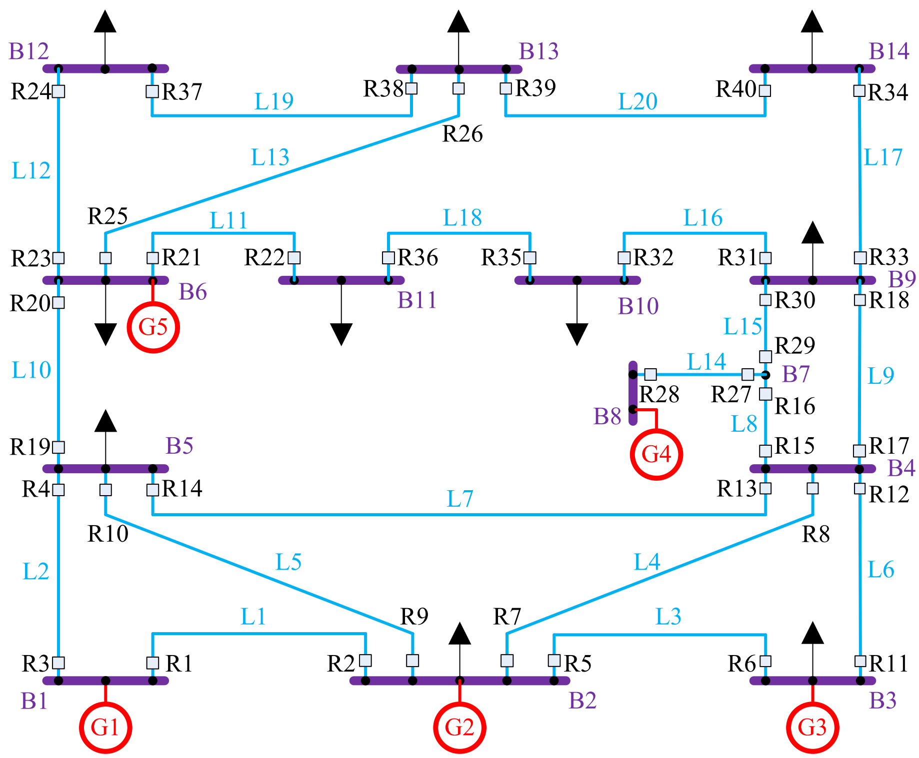

Fig. 4 Protection of arrangement in the IEEE 14 bus test system

ated with the required data preparation. The subsequent four blocks represent the tasks associated with the first stage of GA optimization. The last five blocks are related to obtaining the final solution using IPM. Thus, each relay's optimized values CS, PS and TMS are obtained.

3.2 Considered parameter for the two-stage GA-IPM algorithm

The following necessary parameters have been considered to solve the formulated problem using the developed GA-IPM algorithm:

- TMS range–[0.1, 1.1]
- PS range–[0.5, 2.0]
- Operating time range–[0.1, 4]
- MCT needed–0.2 s
- Population size–200
- Generation number fixed–1000
- Stall generation limit–50
- Tolerance limits on fitness and variables–1e-12

The PS values are in multiples of CT secondary ratings as mentioned [15]. The remaining GA parameters have been considered the same as their default values in the MATLAB optimization toolbox [41]. Similarly, the default parameters specified in the *f*mincon toolbox in MATLAB for the IPM have been employed.

4 Results and discussion

The developed approach has been tested on the IEEE 14-bus and the IEEE 118-bus test systems. A brief system detail and necessary protection arrangements are given in the following subsections, along with the results.

This study uses near-end bolted three-phase-fault currents to calculate the maximum fault currents using the Z_{bus} matrix approach. The minimum fault current has been calculated, corresponding to a far-end line-to-line fault. Further, the Newton–Raphson load flow method has been used to calculate maximum load currents.

4.1 Test results on the IEEE 14-bus system

Figure 4 shows the protection arrangement in the IEEE 14-bus test system. There are 20 lines to interconnect all the buses of this system. Detailed information about the system is available in [42]. In this system, 40 DOCRs (two relays at the end of each line) have 92 combinations of primary backup relationships to protect this power network. The total number of relay pairs considered during the optimization is 53. It is to be noted that some of the primary backup relay combinations have not been considered during the optimization process, as the current passing through the backup relays is less than the corresponding maximum load currents. There are 39 such combinations. The coordination constraints corresponding to these primary backup combinations have been ignored, as the MCT would be maintained.

The setting results obtained for the IEEE 14 bus test system under different sub-cases are given in Tables 5, 6 and 7. The sum of the operating times of all 40 DOCRs corresponding to the maximum fault current passing through the relays and with the obtained setting is also given as the last row of these tables. Also, the CTI between the operating times of primary-backup relay pairs calculated with the optimum settings is shown in Fig. 5. These results are the best results obtained after ten independent runs. A statistical analysis (such as the best value, mean value, worst value of the sum of the operating times of all the relays, standard deviation and time taken by the solver) of the ten runs for each sub-case is given in Table 8.

The summation of operating times of all the 40 DOCRs considering NI and VI type TCC curves are 14.1750 s and 7.7516 s, respectively, higher than the EI type of TCC curve. In the case of EI type TCC, this value is just 6.1625 s. Thus, in the clear from Table 5 in the case of a single TCC curve

Table 5 Optimum settings with same TCC curve for each relay for the IEEE 14-bus test system

Relays	NI curve		VI curve		EI curve	
	TMS	PS	TMS	PS	TMS	PS
1	0.1000	1.0102	0.1000	1.0102	0.1000	1.0102
2	0.1000	0.5000	0.1000	0.5000	0.1107	0.5761
3	0.1000	1.2250	0.1000	1.2250	0.1000	1.2250
4	0.1171	0.5007	0.2872	0.8378	0.6412	1.2471
5	0.1000	1.0906	0.1000	1.0906	0.1000	1.0906
6	0.1000	0.5000	0.1369	0.6752	0.4529	0.9374
7	0.1000	1.0700	0.1000	1.0700	0.1000	1.0700
8	0.1000	0.5000	0.1757	0.8612	0.5450	1.1147
9	0.1127	1.2375	0.1000	1.2375	0.1000	1.2375
10	0.1000	0.5000	0.1329	0.5951	0.3284	0.7935
11	0.1009	0.5006	0.2727	1.1735	0.7929	1.6035
12	0.1000	1.0906	0.1000	1.0906	0.1000	1.0906
13	0.1000	0.5000	0.1923	0.7248	0.5262	1.0161
14	0.1000	1.1958	0.1000	1.1958	0.1000	1.1958
15	0.1284	2.0000	0.2214	0.9292	0.2280	0.9295
16	0.1000	1.5418	0.1000	1.1309	0.2011	0.7658
17	0.1057	2.0000	0.1502	1.1267	0.1496	1.1003
18	0.1933	0.5000	0.3039	0.5000	0.2464	0.5000
19	0.1000	1.3808	0.1000	1.0792	0.1000	1.0792
20	0.1246	2.0000	0.1168	2.0000	0.5239	0.8790
21	0.1365	2.0000	0.1000	1.8619	0.2056	1.0157
22	0.1169	2.0000	0.1000	1.7503	0.2276	1.0144
23	0.1000	1.2401	0.1000	0.8843	0.2056	0.6403
24	0.1000	1.3981	0.1000	0.9916	0.1773	0.6508
25	0.1000	1.9788	0.1000	1.3299	0.1000	1.1188
26	0.1000	0.5000	0.1109	0.5989	0.1983	0.6618
27	0.1000	0.5000	0.1399	0.6226	0.1000	0.5000
28	0.1000	0.5000	0.1000	0.5000	0.1000	0.5001
29	0.1606	0.9250	0.1363	0.9250	0.1121	0.9250
30	0.1000	1.8117	0.1000	1.3384	0.1000	1.2239
31	0.1233	2.0000	0.1000	1.7692	0.1000	1.5066
32	0.1935	1.6769	0.9101	0.5000	1.1000	0.9555
33	0.1000	1.2348	0.2628	0.5000	0.3954	0.5971
34	0.1430	2.0000	0.5953	0.5000	1.1000	0.6348
35	0.1254	2.0000	0.1000	1.8989	0.1000	1.6691
36	0.1619	2.0000	0.1369	2.0000	0.1687	1.5596
37	0.1028	2.0000	0.1000	1.3860	0.2221	0.7682
38	0.1000	1.6560	0.1000	1.2164	0.244	0.7177
39	0.1279	2.0000	0.1000	1.8933	0.1415	1.2737
40	0.1000	1.1427	0.1000	0.8494	0.1929	0.6420
$\sum t_{op}$	14.1750 s		7.7516 s		6.1625 s	

Table 6 Optimum settings considering any two TCC curves options for each relay for the IEEE 14-bus test system

Relays	NI-VI curves			NI-EI curves			VI-EI curves		
	TMS	PS	CS	TMS	PS	CS	TMS	PS	CS
1	0.1001	1.0108	1	0.1029	1.0621	1	0.1000	1.0102	3
2	0.1036	0.7472	1	0.3421	0.8741	3	0.1000	0.5000	3
3	0.1000	1.2253	2	0.1018	1.2713	1	0.1000	1.2250	2
4	0.1024	0.5401	1	0.5295	1.0416	3	0.6933	0.8550	3
5	0.1000	1.0908	2	0.1011	1.1011	1	0.1000	1.0906	2
6	0.1034	0.7259	1	0.4299	0.9106	3	0.4421	0.7431	3
7	0.1000	1.0701	2	0.1013	1.0885	1	0.1000	1.0700	2
8	0.1037	0.5492	1	0.3697	0.8636	3	0.4323	0.8831	3
9	0.1000	1.2377	2	0.1109	1.2743	1	0.1000	1.2375	2
10	0.1041	0.5496	1	0.3644	0.8321	3	0.2107	0.8282	3
11	0.1022	0.9261	1	0.1117	0.9413	1	0.1144	2.000	2
12	0.1001	1.0915	1	0.1033	1.2011	1	0.1000	1.0906	2
13	0.1048	0.5747	1	0.4412	0.9895	3	0.4942	0.8173	3
14	0.1000	1.1960	1	0.1001	1.1978	1	0.1000	1.1958	2
15	0.1609	0.9390	2	0.1084	1.7576	1	0.1000	1.4314	3
16	0.1705	0.9524	1	0.1019	1.3070	1	0.1000	0.9745	3
17	0.1054	1.2326	2	0.1002	1.3941	1	0.1000	1.3378	3
18	0.1649	0.6845	1	0.1201	1.0262	3	0.1000	0.7805	2
19	0.1021	1.1091	1	0.1011	1.1986	1	0.1000	1.0792	2
20	0.4171	0.6806	1	0.1629	1.3257	1	0.1003	2.0000	3
21	0.1230	1.5112	2	0.1377	1.6601	3	0.1000	1.5175	2
22	0.1312	1.4250	1	0.1046	1.1383	1	0.1000	1.6977	3
23	0.1581	0.6293	1	0.1135	1.2050	3	0.1000	0.8307	2
24	0.1798	0.6169	1	0.1240	1.1926	3	0.1000	0.9617	3
25	0.1106	1.2666	1	0.1043	1.5122	3	0.1000	1.1188	2
26	0.1074	0.5600	1	0.4768	0.9506	3	0.1000	0.5000	2
27	0.1035	0.5627	1	0.4344	0.8554	3	0.1000	0.5000	3
28	0.1010	0.5028	1	0.1385	0.5470	3	0.1000	0.5000	3
29	0.1061	0.9252	2	0.1002	0.9367	1	0.1022	0.9250	2
30	0.1158	1.3336	1	0.1122	1.5809	3	0.1000	1.2242	3
31	0.2208	0.9412	1	0.1516	1.4481	3	0.1000	1.5160	3
32	0.1804	0.8610	2	0.1547	1.1488	1	0.7060	0.5000	2
33	0.1054	0.8804	2	0.1227	1.0854	3	0.1000	1.0826	3
34	0.3060	0.9972	1	0.1340	1.0948	1	0.4618	0.5000	2
35	0.3436	0.6538	1	0.1530	1.8280	3	0.1000	1.7063	3
36	0.2077	1.5784	1	0.1410	1.7094	1	0.1099	2.0000	3
37	0.2459	0.6737	1	0.1053	1.1150	1	0.1000	1.1019	2
38	0.2205	0.6299	1	0.1212	1.4149	3	0.1000	0.9946	2
39	0.1493	1.4182	1	0.1290	1.7523	3	0.1000	1.6415	3
40	0.1006	0.5229	2	0.1093	1.2297	3	0.1000	0.8117	2
$\sum t_{op}$	8.5666 s			9.7377 s			5.9412 s		

type, the EI type of TCC curves is to be used as it gives the least operating times of relays.

Similarly, Table 6 shows that the sum of operating times of all 40 relays is the least in the case of VI-EI types of TCC curve options, which is 5.9412 s. This value is even lower than that of only the EI-type TCC curve option. The other two combinations, NI-VI and NI-EI, have relatively higher values of the sum of operating times of relays, which are 8.5666 and

Table 7 Optimum settings obtained with each relay having all the three TCC curves options for the IEEE 14-bus test system

Relays	NI-VI-EI curves			Relays	NI-VI-EI curves		
	TMS	PS	CS		TMS	PS	CS
1	0.1000	1.0102	3	21	0.2234	1.0235	3
2	0.1000	0.5000	3	22	0.1020	1.7497	3
3	0.1000	1.2250	3	23	0.1468	0.7965	3
4	0.4804	0.5000	3	24	0.1000	1.1855	3
5	0.1000	1.0906	2	25	0.1000	1.4177	3
6	0.2752	0.5000	3	26	0.1068	0.5000	3
7	0.1000	1.0700	1	27	0.2274	0.5000	3
8	0.4146	0.5000	3	28	0.1000	0.5000	3
9	0.1000	1.2375	1	29	0.1082	0.9250	1
10	0.3667	0.5000	3	30	0.1000	1.2589	3
11	0.7594	0.5000	3	31	0.1000	0.7400	1
12	0.1176	1.0906	3	32	0.2530	2.0000	3
13	0.2194	0.5000	3	33	0.2507	0.5784	3
14	0.1000	1.1958	3	34	0.1114	2.0000	2
15	0.2815	1.0008	3	35	0.1000	1.7222	3
16	0.1000	1.2767	3	36	0.1793	1.5203	3
17	0.1000	1.6092	3	37	0.1000	1.3724	3
18	0.4222	0.5000	3	38	0.1000	1.4699	3
19	0.1254	1.0792	3	39	0.1000	1.6657	3
20	0.4755	0.9221	3	40	0.1217	0.9147	3
$\sum t_{op}$	5.4622 s						

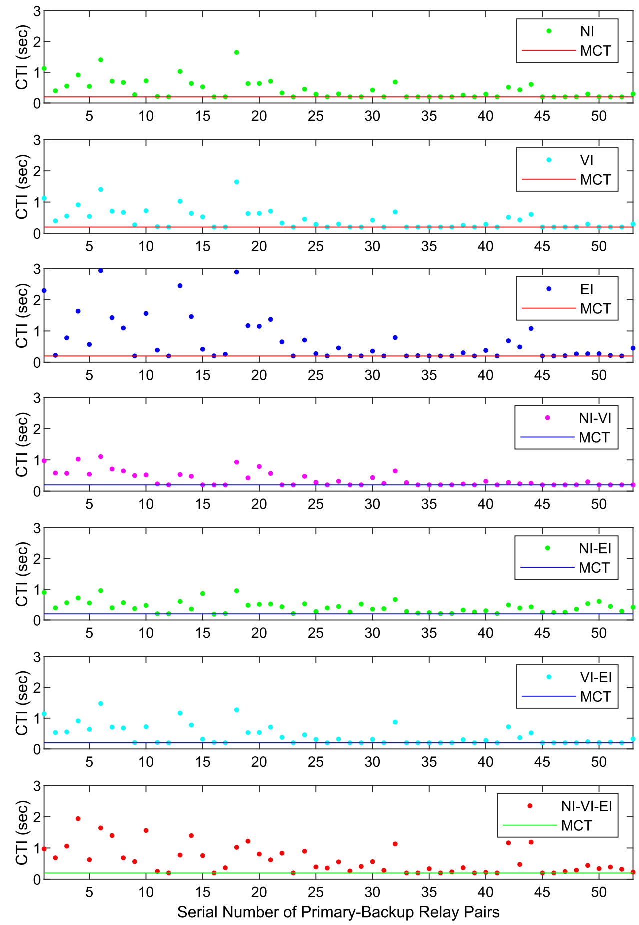

Fig. 5 CTIs of primary-backup relay pairs in various sub-cases with the obtained results for the IEEE 14-bus test system

9.7377 s, respectively. These values are lower than a single NI-type TCC curve for each relay. It is interesting to note that the sum of operating times of all the relays in the case of the NI-VI-EI type of TCC curve option is 5.4622 s. This value is lower than the VI-EI TCC curve and any single-type TCC curve options. This indicates that the optimum setting of the relays is obtained when all three types of TCC curves are considered together, whose settings are given in Table 7. The second best option is the VI-EI type TCC curve, which gives a slightly higher value of the sum of the operating times of all the relays.

The standard deviation corresponding to NI, VI-EI characteristic curves is small compared to the other curves, as seen from Table 8. All primary-backup relay pairs maintain the MCT requirement of 0.2 s, as seen from Fig. 5.

Therefore, the best protection coordination settings are obtained considering the mix of NI, VI, and EI characteristics of DOCRs. The next best type of TCC curve for the relays corresponds to the VI-EI type option. Hence, the optimum protection coordination settings are the TMSs, PSs and CSs values in the last three columns in Table 6 for the IEEE 14-bus systems.

The optimum setting obtained on the IEEE 14 bus test system confirms that the NI-VI-EI types of TCC curves give the best protection coordination settings. The next best option is obtained when VI-EI types of TCC curves are considered.

4.1.1 Proposed algorithm performance study

Results obtained using the proposed two-stage algorithm at the two stages are analysed to check the effectiveness of the developed algorithm. The intermediate and final results obtained under different relay types for the IEEE 14 bus test system are included to analyse the performance. The intermediate results are those obtained using GA by solving the problem as a MINLP problem. The final results are those obtained using IPM by solving the problem as an NLP by keeping the integer variable the same as that obtained using GA. The overall performance is tabulated in Table 9.

4.1.2 Observations on applying mixed characteristic curves

The presented studies on the IEEE 14 bus test system give some essential points to discuss. The following observations

Table 8 Result statistics of 10 independent runs for the IEEE 14-bus test system

Curves	Sum of operating times of relays (sec)			Standard deviation	Average elapsed time (s)
	Best	Mean	Worst		
NI	14.1750	14.2507	14.9299	0.2387	30.39
VI	7.7516	10.0276	16.3796	3.0453	25.71
EI	6.1625	8.0154	11.3480	1.6573	25.34
NI-VI	8.5666	10.5524	13.9653	1.8578	27.71
NI-EI	9.7377	12.2742	20.6763	3.3149	29.06
VI-EI	5.9412	6.6790	8.2985	0.861	28.82
NI-VI-EI	**5.4622**	11.8216	17.5126	5.0227	25.77

Bold data indicates the best data of the row/column

Table 9 Stage-wise GA and GA-IPM performance for best settings for the IEEE 14-bus test system

Particulars	GA (Stage-I)	GA-IPM (Stage-II)	Result improvement
	$\sum t_{op}$ (s)	$\sum t_{op}$ (s)	Reduction in $\sum t_{op}$ (%)
NI	10.8834	7.7516	28.78
VI	**7.1218**	6.1625	13.47
EI	23.2831	14.175	39.12
NI-VI	7.3701	5.9412	19.39
NI-EI	9.9307	9.7377	1.94
VI-EI	11.0327	8.5666	22.35
NI-VI-EI	14.4711	**5.4622**	**62.25**

Bold data indicates the best data of the row/column

are made based on studying mixed characteristic curves of DOCRs for the protection of interconnected power networks.

1. Protection coordination is better with mixed characteristic curves than any single IDMT curve.
2. Very inverse and extremely inverse types of characteristic curves give very low operating times of relays for the maximum fault current. Still, their coordination time intervals are relatively larger, making them unsuitable for practical applications.
3. Study presented on the IEEE 14 bus test system suggests combining very inverse and extremely inverse types of characteristic curves gives the best protection coordination results.
4. Presented studies suggest that the best protection coordination results can be obtained by mixing two relay characteristics for a given interconnected power network.

4.2 Validation on the IEEE 118 bus test system

The proposed approach is applied to the IEEE 118 bus test system to check the performance of the developed algorithm and the effectiveness of the mixed characteristics of the based protection coordination approach. The IEEE 118 bus test system consists of 186 lines and requires 372 DOCRs to protect this system, as shown in Fig. 6.

In this test system, there are a total of 1148 primary backup relay pairs. A total of 829 primary backup relay pairs have been considered in the optimization. In the remaining pairs, fault currents passing through the backup relays are very small, and hence, their operating times are large, so minimum coordination tire requirement is always maintained. The necessary data for this test system is available in [42]. Various load and fault currents data, primary-backup relay pairs and other data are calculated using the same approach previously [14].

4.2.1 Results on the IEEE 118-bus test system

The optimum settings obtained considering mixed characteristics (NI-VI-EI) of DOCRs are shown in Fig. 7. Statistical results of 10 independent runs of the developed GA-IPM algorithm for solving the protection coordination problem of the IEEE 118 bus test system are given in Table 10.

4.2.2 Comparison of results of the IEEE 118-bus test system

The sum of the operating times of 372 relays used to protect the IEEE 118 bus test system using mixed-curve types

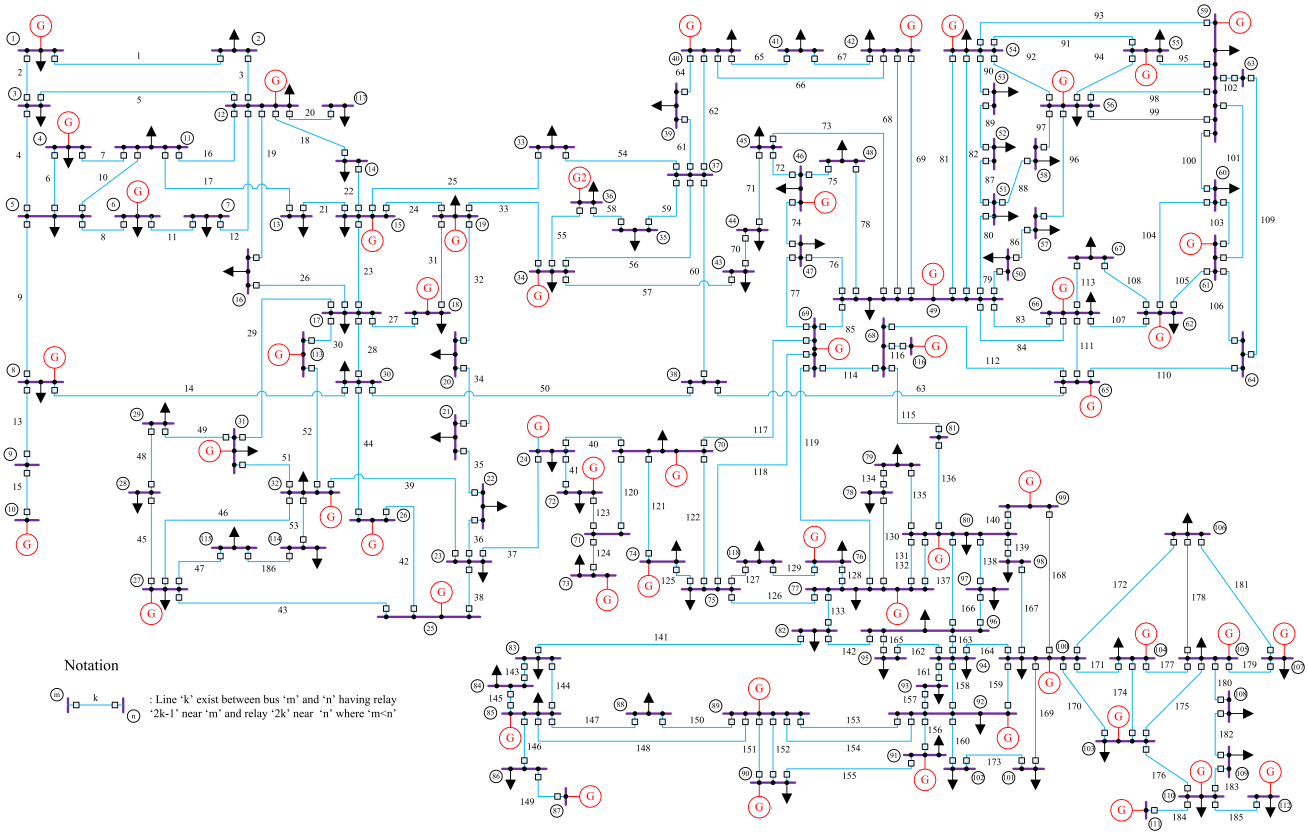

Fig. 6 IEEE 118-bus test system

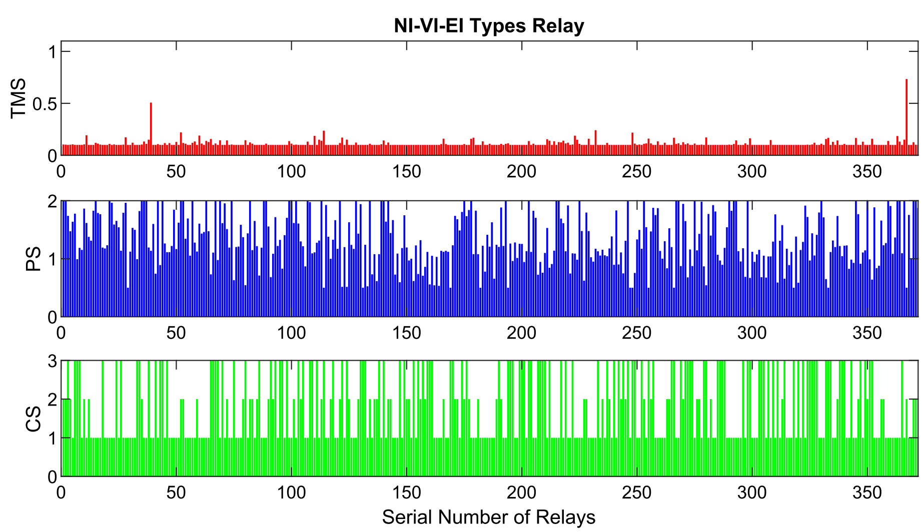

Fig. 7 Optimum setting of relays considering NI-VI-EI types TCCs for the IEEE 118 bus system

Table 10 Result statistics of 10 independent runs for the IEEE 118 bus test system

Curves	Sum of operating times of relays (s)			Standard deviation	Average elapsed time (s)
	Best	Mean	Worst		
NI-VI-EI	**68.8312**	79.9659	84.9263	5.11	3844.79

Bold data indicates the best data of the row/column

DOCRs and the developed algorithm is 68.8312 s. The best results obtained for the protection coordination of this system are reported in [14], which is 99.0291 s. Here, the reduction in the sum operating times of relays is 30.5%, which is considerable. Mixed characteristics have also been used in [14]. However, the curve types have been considered randomly in the literature. In the proposed approach, curve type has been considered as a separate variable and optimally selected. This is the main reason for the excellent performance of the proposed approach as compared to that available in the literature.

4.3 Future scope the work

As the developed algorithm can solve complicated protection coordination problems effectively, the same can be applied to solve the protection coordination problem of modern power systems with high penetration of low inertia renewable (converter-based Solar and Wind power plants) power generations. Because of the addition of renewable sources, fault currents are reduced, which creates many issues for conventional relays, which cannot operate faster. The selection of proper TCC and their optimum setting calculation to even operate the relay adequately faster with proper coordination, the developed formulation and the solution methodology can be utilized. The future scope of this work includes applying the considered problem formulation and the developed algorithm to solve the protection coordination problem of power distribution networks with high penetration of low inertia electric power generations from converter-based solar and wind sources.

5 Conclusion

This paper presents optimum characteristic selection and setting computation of directional overcurrent relays. The proposed protection coordination approach has been tested on the IEEE 14-bus and 118-bus test systems. Based on the studies presented in this work, it has been observed that the combination of two different types of characteristic curves of relays gives the best protection coordination results. The combination of very inverse and extremely inverse types of characteristic curves of relays performs well on relatively smaller systems. In contrast, the combination of normal inverse and very inverse types of characteristic curves provides better protection coordination than any single characteristic curve or any other combination of normal inverse, very inverse and extremely inverse.

Further study will focus on considering high renewable penetration and analysing their impact on mixed-characteristic curves based on directional overcurrent relays-based protection schemes.

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Data availability The data and materials used in this work are reported already in the paper. Any additional data asked for by the journal can be made available.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval The presentation work does not involve human and/or animal studies.

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