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Optimal Relay Coordination for DG-Based Power System Using Standard and User-Defined Relay Characteristics

Raghvendra Tiwari*, Ravindra Kumar Singh, Niraj Kumar Choudhary

Electrical Engineering Department, Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India

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Abstract

The operating time of directional overcurrent relays (DOCRs) can be reduced with user-defined relay characteristics considering plug setting (PS), time multiplier setting (TMS), and relay characteristic coefficients (λ and γ). This study presents a comparative analysis of relay coordination with standard and user-defined relay characteristics. The proposed relay coordination scheme is formulated as a non-linear constraint optimization problem. The grey wolf optimization (GWO) algorithm is used to determine the optimal relay settings and total operating time of DOCRs. The performance of the proposed scheme is tested on the standard 8-bus, 9-bus, and 15-bus systems. The results show that the total operating time of DOCRs with user-defined relay characteristics is better than that with standard relay characteristics. The results of the GWO algorithm are compared with the performance of optimization techniques used in literature to solve the relay coordination problem.

Keywords: coordination time interval, grey wolf optimization, plug setting, relay coordination, time multiplier setting

1. Introduction

Protection schemes play a crucial role in the smooth functioning and reliable operation of a power system network. A protection scheme must be able to detect faults and isolate the faulty section, maintaining the sustainability of supply in the healthy section. To establish an effective protection scheme, each relay of the system is to be synchronized with its corresponding backup relay. Relay coordination may be defined as a correct operating sequence of relays for removing the faults. The key objective for the optimum coordination of directional overcurrent relays (DOCRs) is to reduce the operating time of primary relays, achieving the selectivity criterion between primary-backup relay pairs (PBRPs) without any miscoordination of relay pairs.

The relays placed near the fault location and mainly responsible for operating first under the faulty condition are known as primary relays. If primary relays fail to operate, the relays located on the nearby branch, sensing the same fault, will work as backup relays. A fixed minimum time delay is provided between the backup and primary relays to avoid any miscoordination issues. This time interval is termed as the coordination time interval (CTI). The value of CTI for conventional (electromechanical) and microprocessor-based relays is in the range of 0.3-0.6 s and 0.2-0.5 s, respectively.

DOCRs are used as the primary protection devices for distribution networks due to their simple operation and cheap maintenance. However, they are used as backup protection devices for transmission networks due to their sluggish operation. The DOCRs' operating time mainly depends on two parameters, namely, plug setting (PS) and time multiplier setting (TMS). The conventional DOCRs are available with standard relay characteristics such as extremely inverse (EI), very inverse (VI), normal inverse (NI), and long inverse (LI) [1]. Depending on the relay characteristics, the relay characteristics coefficients (λ and γ) have specific values as per the IEC-60255 standard.

* Corresponding author. E-mail address: raghvendra@mnnit.ac.in

The prime limitations of conventional DOCRs are that they can have only one specified standard relay characteristic among NI, VI, and EI. Also, they are bounded to select only discrete values of PS. Microprocessor-based relays are widely used in modern distribution networks to overcome these limitations. The microprocessor-based relays can adopt user-defined relay characteristics according to the system requirements, and they can have a continuous value of TMS and PS within the predefined limits [2]. In user-defined relay characteristics, the values of λ and γ are optimally chosen along with TMS and PS to achieve the optimal relay coordination.

Various methods are available in the literature to solve the relay coordination problem. These methods are classified as topological, trial and error, and optimization methods. The trial and error method is not a practical solution for relay coordination problems due to the requirement of several iterations, massive computation, and a slow convergence rate. Also, the solution obtained by this method is not optimal. In the topological method, fewer iterations are required to compute the relay settings. The main drawback is the requirement of relay break-points to initiate the relay coordination process [3]. However, the solutions obtained by optimization methods are more accurate and optimal. The optimization method is classified according to the selection and nature of decision variables as linear, non-linear, and mixed-integer non-linear programming (MINLP).

In the linear programming method, only TMS is taken as a continuous variable while PS is kept fixed based upon previous experiences [4]. Using the linear programming approach, researchers found the optimal values of TMS by using various optimization algorithms such as the Big-M [5], dual simplex [6], modified JAYA algorithm [7], etc. In the non-linear programming method, TMS and PS are both taken as decision variables. By considering the non-linear programming approach, researchers found the optimal relay settings, i.e., both TMS and PS, by using firefly algorithm and genetic algorithm (GA) [8], advanced teaching-learning based optimization (ATLBO) [9], gravitational search algorithm (GSA) [10], sequential quadratic programming (SQP) [11], RAO-I algorithm [12], multiple sequence alignment (MSA) [13], etc. The solutions obtained by the non-linear method are more accurate when compared to linear methods. In the MINLP approach, PS and TMS are taken as discrete and continuous variables, respectively.

This research aims to perform a comparative analysis of optimal relay coordination problems by considering the standard and user-defined relay characteristics in the 8-bus, 9-bus, and 15-bus test systems. The comparison of the total relay operating time with standard and user-defined relay characteristics using the grey wolf optimization (GWO) algorithm differentiates this study from other existing research available in the literature. The obtained results are compared with the different optimization techniques to validate the efficacy of the proposed technique. The study is divided into four sections. Section 2 describes the relay coordination problem formulation, section 3 presents the results obtained by the GWO technique, and lastly, the study is concluded in section 4.

2. Problem Formulation

The main objective of the relay coordination problem is to minimize the total relay operating time while maintaining the criterion of selectivity. The overcurrent relay coordination problem in large distribution networks becomes more complicated and computationally intensive due to the large number of PBRPs. The following conditions must be satisfied to find optimal solutions for the relay coordination problem.

(1) The measured coordination time (MCT) should be more than the considered CTI for each PBRP.

(2) The primary relay should not operate before the predefined minimum operating time.

(3) If the primary relay fails to operate, no other relays should operate except the corresponding backup relay.

2.1. Objective function

The objective function (OF) for the relay coordination problem is formulated as the summation of the operating times of all primary relays as given by Eq. (1) [14]. For the user-defined relays, the values of λ and γ can be selected according to the system requirements within the prescribed limits, as shown in Table 1. Therefore, the number of decision variables is more for user-defined relays as compared to the standard relays. Due to this, the relay coordination problem with user-defined relay characteristics is more flexible than the standard relay characteristics.

$$OF = Min \sum_{i=1}^{N} t_{i,k} \tag{1}$$

$$t_{i,k} = \frac{\lambda^i \times TMS^i}{\left(\dfrac{I_f}{PS^i \times CTR^i}\right)^{\gamma^i} - 1} \tag{2}$$

In Eq. (1), $t_{i,k}$ represents the operating time of the i^{th} primary relay for k^{th} fault location. In Eq. (2), I_f represents the fault current magnitude, CTR^i is the current transformer ratio (CTR). TMS^i and PS^i are time multiplier setting and plug setting respectively for the i^{th} primary relay.

Table 1 Relay characteristic coefficients as per IEC-60255 standard

Serial number	Relay characteristics	λ^i	γ^i
1	Extremely inverse (EI)	80	2
2	Very inverse (VI)	13.5	1
3	Normal inverse (NI)	0.14	0.02
4	Long inverse (LI)	120	1

2.2. Coordination constraints

The relay coordination problem aims to obtain the optimal settings for which the total relay operating time is minimum. The relay coordination is a constraint optimization problem that satisfies specific non-linear constraints to get optimal relay settings. The non-linear constraints are formulated by considering the permissible range of decision variables and the selectivity criterion.

2.2.1. Boundary condition for decision variables

The obtained values of TMS, PS, λ, and γ for microprocessor-based DOCRs must lie within the maximum and minimum values provided by the relay manufacturers as shown by Eqs. (3)-(6). The minimum and maximum limits of λ are taken as 0.14 and 120, and the minimum and maximum limits of γ are 1 and 2 respectively [14].

$$TMS^i_{\min} \le TMS^i \le TMS^i_{\max} \tag{3}$$

$$PS^i_{\min} \le PS^i \le PS^i_{\max} \tag{4}$$

$$\lambda^i_{\min} \le \lambda^i \le \lambda^i_{\max} \tag{5}$$

$$\gamma^i_{\min} \le \gamma^i \le \gamma^i_{\max} \tag{6}$$

2.2.2. Bounds on primary relay operating time

The primary relays must operate between the pre-defined minimum and maximum limits of the relay operating time as given by Eq. (7). In this study, the minimum and maximum operating times of primary relay have been considered 0.1 s and 2 s respectively [14]. The maximum relay operating time depends on the critical clearing time (CCT) for a particular fault to ensure the power system stability [15].

$$t_{\min} \le t_{i,k} \le t_{\max} \tag{7}$$

2.2.3. Selectivity constraints

For a proper relay coordination scheme, the backup relay operating time must be more than the primary relay operating time by a margin of CTI as represented by Eq. (8). In Eq. (8), $t_{i,k}$ and $t_{j,k}$ are the operating time of i^{th} primary and j^{th} backup relay respectively for the fault at k^{th} location.

$$t_{j,k} - t_{i,k} \geq CTI \tag{8}$$

After the formulation of OF and the constraints, the next step is to determine the optimal solution for the relay coordination problem. In this study, GWO has been used to determine the optimal settings of user-defined DOCRs, which is mentioned in the subsequent section.

2.3. Grey wolf optimization

The prime concept behind the operating principle of GWO is the living tendency of grey wolves. The grey wolves are categorized into four subdivisions such as alpha (α), beta (β), delta (δ), and omega (ω), as shown in Fig. 1 [16]. The α wolf is known as the best, which can make the most crucial decision of the pack related to hunting. The α wolf is very experienced and can manage the whole group efficiently. The second best is the β wolf, which helps α while making a decision and also command the other lower-level wolves. The third best is the δ wolf, which gives the assistance to α and β but overrides ω. All other candidates are assumed as ω wolves, which follow all the decisions taken by the other dominant wolves.

The hunting phenomenon is guided by α, β, and δ. The main steps of the GWO technique are chasing the prey, surrounding the prey in the form of a circle, and attacking the prey. Mathematically, encircling the prey is represented by Eqs. (9)-(10).

$$D = \left| \overline{C} \cdot \overline{X_p(t)} - \overline{X(t)} \right| \tag{9}$$

$$X(t+1) = \overline{X_p(t)} - \overline{A} \cdot \overline{D} \tag{10}$$

In Eqs. (9)-(10), t represents the current running iteration, $X(t)$ and $X(t+1)$ represents the current and updated position of the ω grey wolf, $X_p(t)$ refers to the estimated position of prey, D is the distance between the grey wolf and prey, and R is the radii of hyper-sphere that defines the prey's estimated position. In Eq. (11), the "a" component decreases linearly from 2 to 0 over the iteration. In Eqs. (12)-(13), the random vectors r_1 and r_2 lie in the range of [0, 1] and the vectors A and C represents the coefficient vectors.

$$a = 2\left(1 - \frac{current\_iteration}{maximum\_iteration}\right) \tag{11}$$

$$\overline{A} = 2\overline{a} \cdot \overline{r_1} - \overline{a} \tag{12}$$

$$\overline{C} = 2 \cdot \overline{r_2} \tag{13}$$

The search agents ω follow α, β, and δ and update their position according to the position of the best agent by adjusting "A" and "C" vectors. To mathematically simulate the hunting manner of a wolf pack, the role of top three best solutions (α, β, and δ) is fixed to allow other search agents ω to modify their position accordingly [17].

The coefficient vector "A" lies randomly in the range [-2a, 2a]. For searching prey, $|A|$ should be greater than 1, and for attacking prey, $|A|$ should be less than 1. In this study, the numbers of search agents and maximum iteration are considered 50 and 1500 respectively. The flowchart of the proposed optimal relay coordination scheme is shown in Fig. 2.

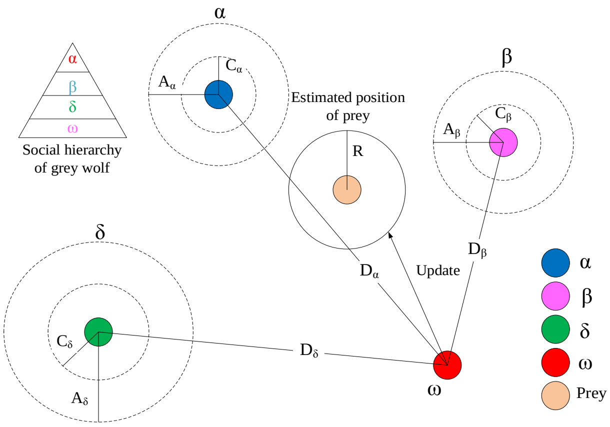

Fig. 1 Social hierarchy and steps of GWO [16]

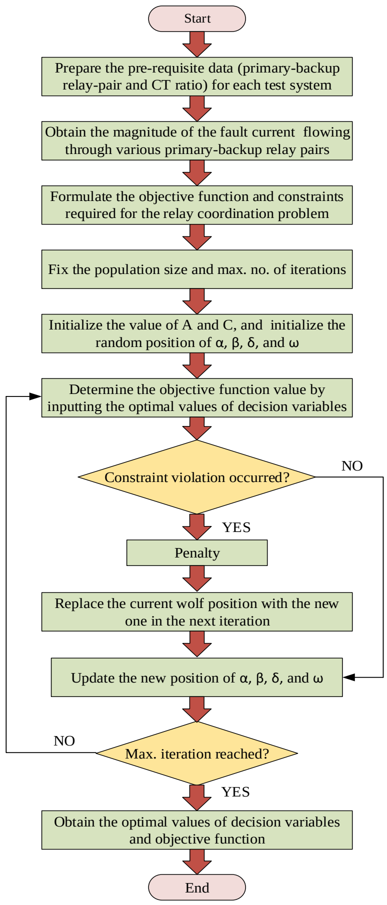

Fig. 2 Flowchart of the proposed relay coordination scheme

3. Results and Discussion

The performance of the proposed relay coordination scheme has been tested on three test systems, namely, 8-bus, 9-bus, and 15-bus test systems. The simulation has been performed in MATLAB R2018a. To show the efficacy of the proposed scheme, the operating range of decision variables is kept the same as considered for conventional DOCRs in the base paper.

3.1. 8-bus test system

The 8-bus test system consists of nine lines and two generators, as shown in Fig. 3. Each line is protected by two DOCRs placed at both ends of the line. With this assumption, 14 DOCRs are required to protect the whole system. The line connecting Bus1 to Bus7 and Bus6 to Bus8 through transformer T_1 and T_2 does not have any relay because of the inbuilt protection features of the transformers. The MVA capacity of the generators G_1 and G_2 is 150 MVA each. All the other test system details are taken from the work of Ezzeddine et al. [18]. The total number of PBRPs for different fault locations considered (F1, F2, ……, F14) is found to be 20, as shown in Table 2. The operating range of TMS and PS are considered [0.05-1.1] and [0.5-2.5] respectively [18]. The value of CTI is considered 0.3 s. The optimal relay settings obtained by the GWO algorithm with NI, VI, and user-defined relay characteristics are shown in Table 3. The decision variables for conventional DOCRs are selected as PS_1-PS_{14} and TMS_1-TMS_{14} for the relays R1-R14. For microprocessor-based relays, the decision variables are chosen as PS_1-PS_{14}, TMS_1-TMS_{14}, λ_1-λ_{14}, and γ_1-γ_{14}.

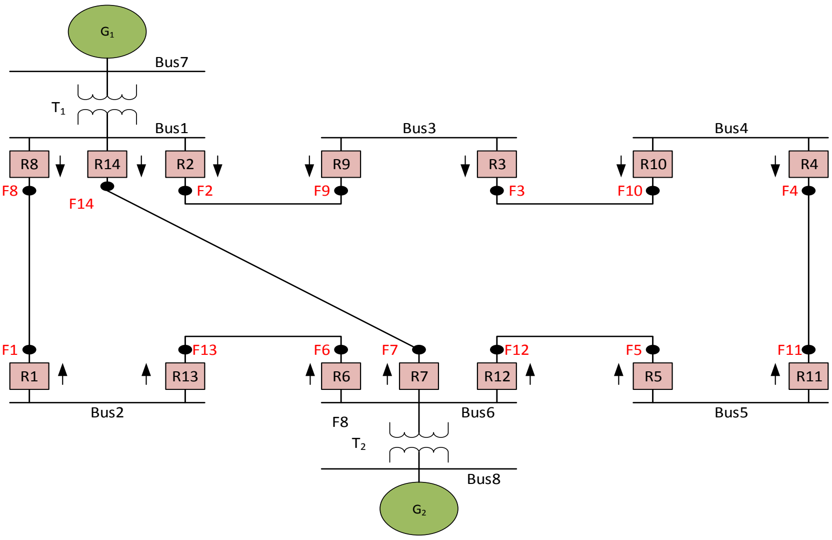

Fig. 3 The 8-bus test system

Table 2 PBRPs of the 8-bus test system

Fault point (F)	Relay pair (RP)	Primary relay	Backup relay	Fault point (F)	Relay pair (RP)	Primary relay	Backup relay
F1	RP1	R1	R6	F8	RP11	R8	R7
F2	RP2	R2	R1	F8	RP12	R8	R9
F2	RP3	R2	R7	F9	RP13	R9	R10
F3	RP4	R3	R2	F10	RP14	R10	R11
F4	RP5	R4	R3	F11	RP15	R11	R12
F5	RP6	R5	R4	F12	RP16	R12	R13
F6	RP7	R6	R5	F12	RP17	R12	R14
F6	RP8	R6	R14	F13	RP18	R13	R8
F7	RP9	R7	R5	F14	RP19	R14	R1
F7	RP10	R7	R13	F14	RP20	R14	R9

Table 3 Optimal settings of DOCRs with NI, VI, and user-defined relay characteristics obtained by using GWO

Relay	NI characteristics		VI characteristics		User-defined relay characteristics			
	TMS	PS	TMS	PS	TMS	PS	λ	γ
R1	0.0511	2.3617	0.0611	1.4991	0.0913	1.3036	41.9749	1.7134
R2	0.3018	1.2306	0.2345	2.2669	0.3802	0.9079	104.9713	1.6080
R3	0.2573	0.8721	0.2473	1.8011	0.4321	1.5188	68.6268	1.9140
R4	0.0680	2.2530	0.0505	2.0842	0.0672	1.7563	53.7053	1.9990
R5	0.0503	1.1494	0.0534	0.7245	0.0926	1.3743	4.2433	1.1394
R6	0.2194	0.6648	0.1319	2.1643	0.3008	2.1915	18.9005	1.6705
R7	0.2094	2.2953	0.2620	1.5316	0.8014	1.5351	33.8054	1.9622
R8	0.1452	1.6575	0.4901	0.6503	0.5002	2.0020	21.7625	1.9853
R9	0.0501	1.8619	0.1207	0.6431	0.4333	2.1244	0.7606	1.0124
R10	0.0665	2.4454	0.1568	0.9958	0.0543	1.6401	89.6678	1.9998
R11	0.2527	0.6413	0.5608	0.6467	0.8421	2.3678	7.5491	1.9417
R12	0.2252	2.3434	0.3485	1.7676	0.7948	1.2986	75.4632	1.9920
R13	0.0501	2.4461	0.0504	1.7548	0.0807	1.7938	39.1443	1.9905
R14	0.1931	2.4726	0.7709	0.6392	1.0248	1.2196	47.3174	1.9999
OF	6.0313 s		3.2720 s		1.9627 s			

From Table 3, it can be seen that the total relay operating time obtained by the GWO algorithm for NI, VI, and user-defined relay characteristics is found to be 6.0313 s, 3.2720 s, and 1.9627 s, respectively. It can be observed that the total operating time of the relay decreases as the relay characteristics change from NI to user-defined. The primary and backup relays' operating time obtained with NI, VI, and user-defined relay characteristics is shown in Figs. 4-6, respectively. The primary and backup relay operating times for different fault locations are included in Appendix (Table A). Further, for each relay pair (RP1-RP20), the operating time of the backup relay is larger than the corresponding primary relay. The difference between the operating time of primary and backup relay is consistently found to be more than the considered CTI value (0.3 s) for all the relay characteristics, authenticating the proper relay coordination among the DOCRs.

In user-defined relays, TMS, PS, and the relay coefficients (λ and γ) are optimally selected within their prescribed minimum and maximum limits. The results obtained with user-defined relay characteristics are best in terms of the total operating time of relays when compared to the results obtained with other standard relay characteristics. The OF value obtained with NI relay characteristics by the GWO algorithm and other optimization algorithms such as EFO [19], MEFO [19], DE [20], HS [21], PSO [20], WCA [22], MWCA [22], BH [23] are shown in Fig. 7. It can be seen that the value of OF is least (6.0313 s) with the GWO algorithm. The OF value obtained with user-defined relay characteristics by the GWO algorithm is 1.9627 s, which is less than the OF value obtained using IMFO [14]. The convergence plot of the GWO algorithm for the 8-bus test system for NI, VI, and user-defined relay characteristics is shown in Fig. 8. From the convergence plot, it can be seen that fewer iterations are required in the case of user-defined relay characteristics compared to the standard relay characteristics to get the optimal OF values.

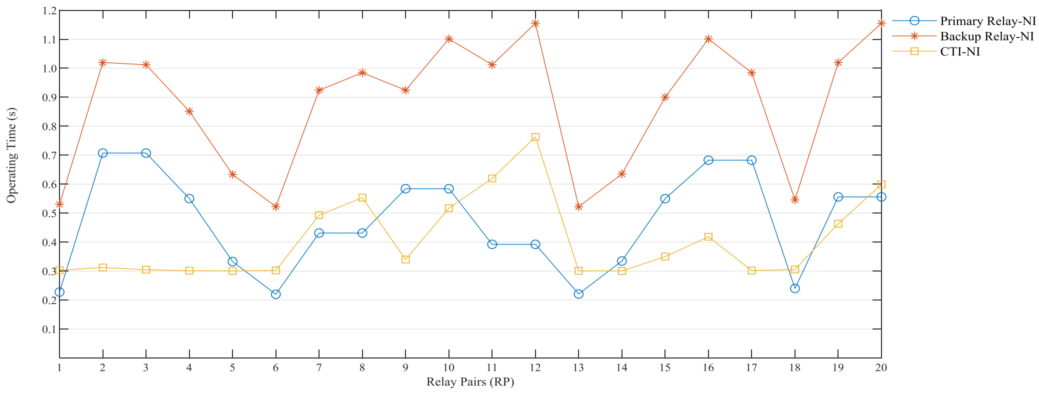

Fig. 4 Relay operating time with NI relay characteristics obtained by using GWO

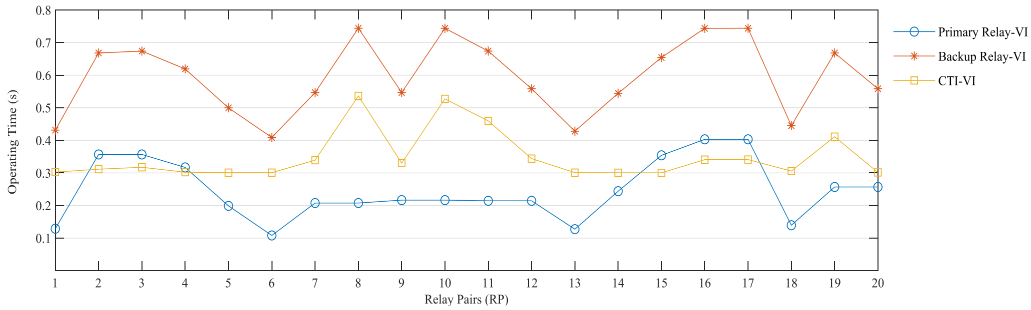

Fig. 5 Relay operating time with VI relay characteristics obtained by using GWO

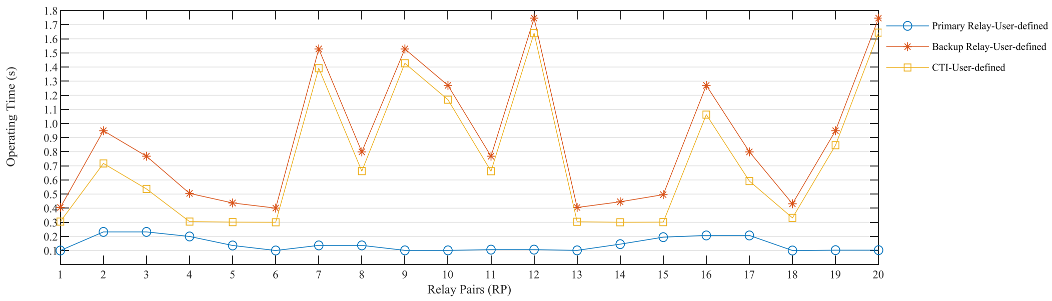

Fig. 6 Relay operating time with user-defined relay characteristics obtained by using GWO

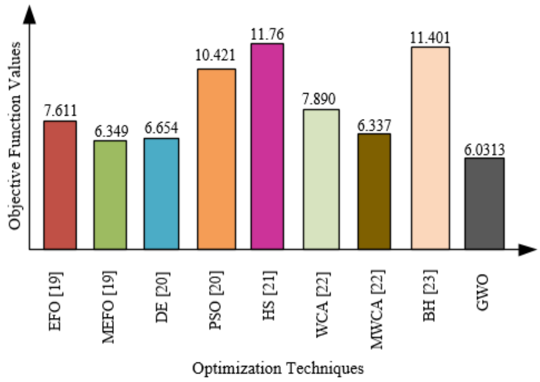

Fig. 7 Comparative analysis of the OF value with standard NI relay characteristics using different optimization techniques

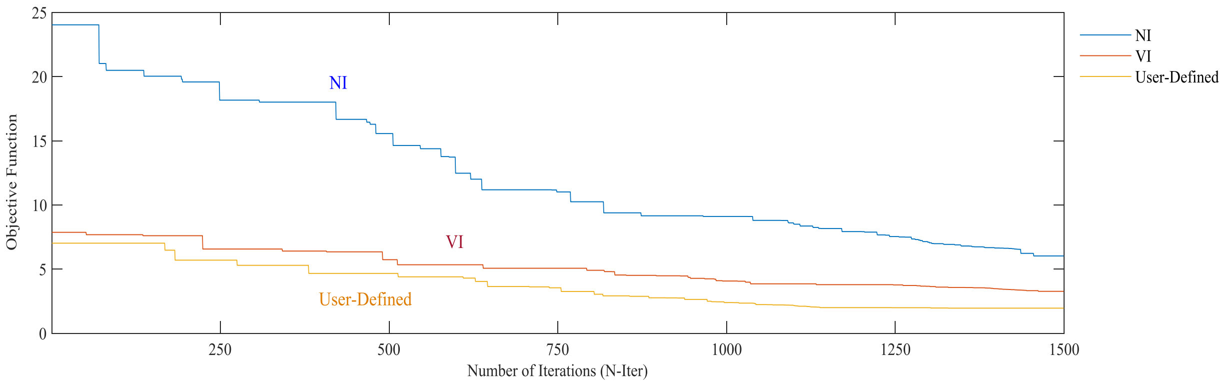

Fig. 8 Convergence plot of GWO with NI, VI, and user-defined relay characteristics

3.2. *9-bus test system*

The 9-bus test system consists of twelve lines and a single generator, as shown in Fig. 9. Each line is protected by two DOCRs placed at both ends of the line, so the total number of DOCRs required to protect all the lines is 24. An external source of rating 100 MVA, 33 kV having an impedance of (0+j0.1) pu is connected to Bus1. The CTR of all the DOCRs is the same for all the relay characteristics and is considered 500:1. Base MVA and base kV are taken as 100 MVA and 33 kV, respectively. All the other test system details are taken from the work of Bedekar et al. [24]. The operating range of TMS and PS are considered [0.025-1.2] and [0.5-2.5], respectively. The CTI value is taken as 0.2 s. The 9-bus test system consists of 30 PBRPs (RP1-RP30) for different fault locations (A, B, ……, L), as shown in Table 4. The decision variables for conventional DOCRs are taken as PS_1-PS_{24} and TMS_1-TMS_{24} for the relays R_1-R_{24}. For microprocessor-based relays, the decision variables are considered PS_1-PS_{24}, TMS_1-TMS_{24}, λ_1-λ_{24}, and γ_1-γ_{24}.

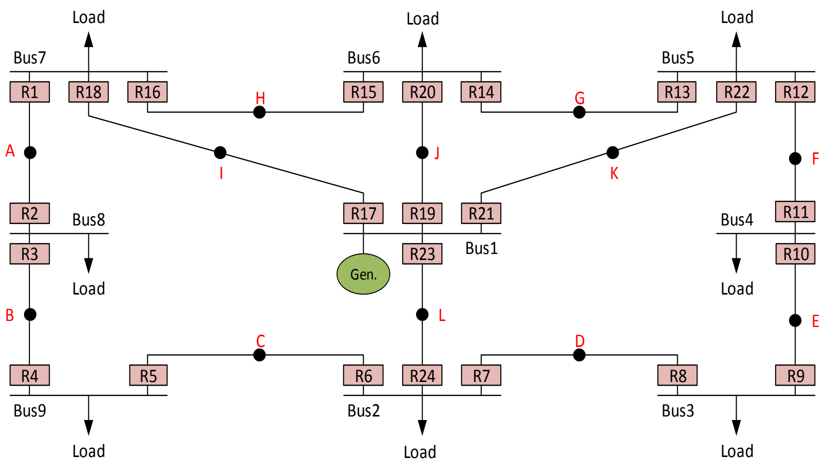

Fig. 9 The 9-bus test system

Table 4 PBRPs of the 9-bus test system

Fault point (F)	Relay pair (RP)	Primary relay	Backup relay	Fault point (F)	Relay pair (RP)	Primary relay	Backup relay	Fault point (F)	Relay pair (RP)	Primary relay	Backup relay
A	RP1	R1	R15	D	RP11	R8	R10	H	RP21	R16	R2
A	RP2	R1	R17	E	RP12	R9	R7	H	RP22	R16	R17
A	RP3	R2	R4	E	RP13	R10	R12	I	RP23	R18	R2
B	RP4	R3	R1	F	RP14	R11	R9	I	RP24	R18	R15
B	RP5	R4	R6	F	RP15	R12	R14	J	RP25	R20	R13
C	RP6	R5	R3	F	RP16	R12	R21	J	RP26	R20	R16
C	RP7	R6	R8	G	RP17	R13	R11	K	RP27	R22	R11
C	RP8	R6	R23	G	RP18	R14	R21	K	RP28	R22	R14
D	RP9	R7	R5	H	RP19	R15	R13	L	RP29	R24	R5
D	RP10	R7	R23	H	RP20	R15	R19	L	RP30	R24	R8

Table 5 Optimal settings of DOCRs with NI, VI, and user-defined relay characteristics obtained by using GWO

Relay	NI characteristics		VI characteristics		User-defined relay characteristics			
	TMS	PS	TMS	PS	TMS	PS	λ	γ
R1	0.0251	1.7432	0.0290	1.9831	0.1028	0.5326	23.7760	1.1144
R2	0.0250	0.7420	0.0408	0.5016	0.0487	0.6622	15.8533	1.3424
R3	0.0250	1.3961	0.0808	0.5454	0.2152	0.6610	5.9490	1.2158
R4	0.0252	1.1953	0.0659	0.5276	0.1736	1.6218	2.3798	1.3982
R5	0.0250	1.2551	0.0251	1.0534	0.1012	1.1231	8.4800	1.9435
R6	0.0250	1.5790	0.0469	1.1974	0.0818	0.7552	110.0542	1.8396
R7	0.0256	1.5084	0.0620	0.9370	0.3472	0.5203	7.0935	1.1488
R8	0.0250	1.2556	0.0703	0.5390	0.2351	1.2201	3.1660	1.9287
R9	0.0257	1.2016	0.0387	0.8415	0.4894	0.7616	2.5103	1.3362
R10	0.0250	1.3931	0.0461	0.8358	0.0480	0.8424	73.2397	1.8881
R11	0.0251	0.7342	0.0397	0.5139	0.2327	0.8993	1.4054	1.1222
R12	0.0259	0.9628	0.0496	0.7308	0.0547	0.8821	60.4085	1.9048
R13	0.0253	1.2967	0.0456	1.0286	0.0285	1.6582	49.6398	1.8199
R14	0.0255	1.4585	0.1123	0.5173	0.7853	1.5624	2.4539	1.7945
R15	0.0312	1.2560	0.0618	0.8983	0.2872	1.2954	3.5194	1.2919
R16	0.0275	1.1138	0.1086	0.5001	0.3375	0.5560	24.5221	1.7141
R17	0.0401	1.0258	0.2102	0.5200	0.0743	1.5540	13.4722	1.0501
R18	0.0250	0.8170	0.0420	0.6858	0.0351	1.5602	18.5152	1.8832
R19	0.0379	1.1253	0.1242	0.8373	0.8553	0.9501	2.6533	1.1498
R20	0.0250	0.9755	0.0335	0.9500	0.0738	1.2808	8.0317	1.3674
R21	0.0302	1.9815	0.0608	1.6555	0.1797	0.6287	30.6230	1.2607
R22	0.0275	0.6898	0.0433	0.6671	0.6206	1.9444	0.3050	1.2374
R23	0.0325	1.7303	0.1243	0.8962	0.4676	0.5984	14.8445	1.2984
R24	0.0254	0.5818	0.0419	0.5003	0.0345	1.1175	23.2921	1.9950
OF	2.6743 s		2.5518 s		2.4296 s			

The optimal settings of DOCRs obtained by the GWO technique in the 9-bus test system for NI, VI, and user-defined relay characteristics are shown in Table 5. The results show that the total relay operating time with NI, VI, and user-defined relay characteristics are 2.6743 s, 2.5518 s, and 2.4296 s, respectively. It can be observed that the total operating time of the relay reduces as the relay characteristics change from NI to user-defined.

The primary and backup relay operating times obtained with NI, VI, and user-defined relay characteristics are shown in Figs. 10-12, respectively. The primary and backup relay operating times for each relay pair for different fault locations are given in Appendix (Table B). The results show that for each relay pair (RP1-RP30), the backup relay operating time is more than the corresponding primary relay. The difference between the primary and backup relay operating time is always more than the considered CTI (0.2 s) for all the relay characteristics. It can be observed that the performance of the user-defined relays is better in terms of the total relay operating time and the backup relay operating time as compared to the conventional relays. The obtained results reveal that the total relay operating time achieved by the GWO algorithm with user-defined relay characteristics is least compared to all other relay characteristics.

The obtained OF values with NI characteristics using the GWO algorithm and other existing optimization techniques such as MFO [14], IMFO [14], EFO [19], MEFO [19], DE [20], GA [20], PSO [20], HS [21], WCA [22], MWCA [22], BH [23], GA-NLP [24], BBO-LP [25], GSA [26], SQP [26], GSA-SQP [26], IFA [27], FA [27], are shown in Fig. 13. It can be seen that the OF value is the least (2.6743 s) with the GWO algorithm. Also, the OF value obtained with user-defined relay characteristics by the GWO algorithm is 2.4296 s which is less than the OF value obtained by IMFO [14]. The convergence plot of the GWO for the 9-bus test system with NI, VI, and user-defined relay characteristics is shown in Fig. 14. From the convergence plot, it can be seen that fewer iterations are required in the case of user-defined relay characteristics as compared to the standard relay characteristics to get the optimal OF values.

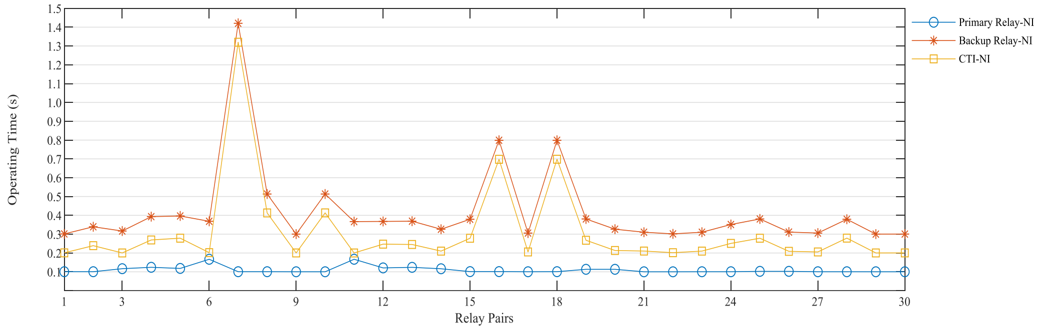

Fig. 10 Relay operating time with NI relay characteristics obtained by using GWO

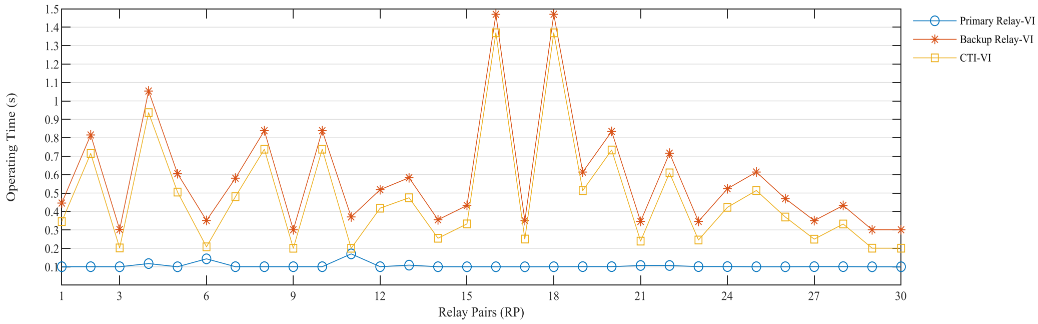

Fig. 11 Relay operating time with VI relay characteristics obtained by using GWO

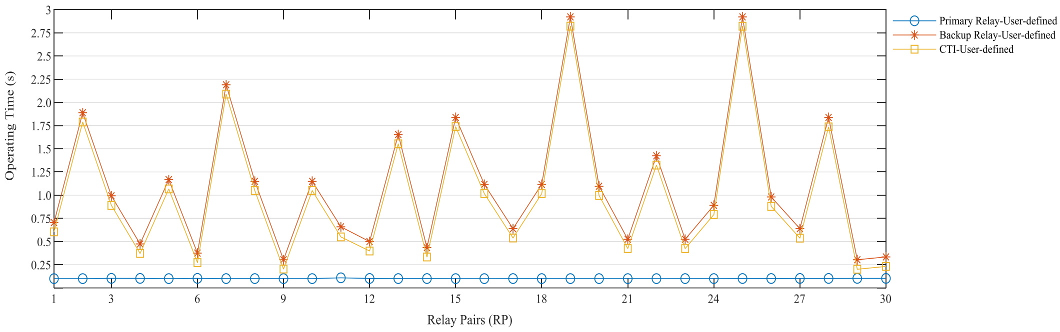

Fig. 12 Relay operating time with user-defined relay characteristics obtained by using GWO

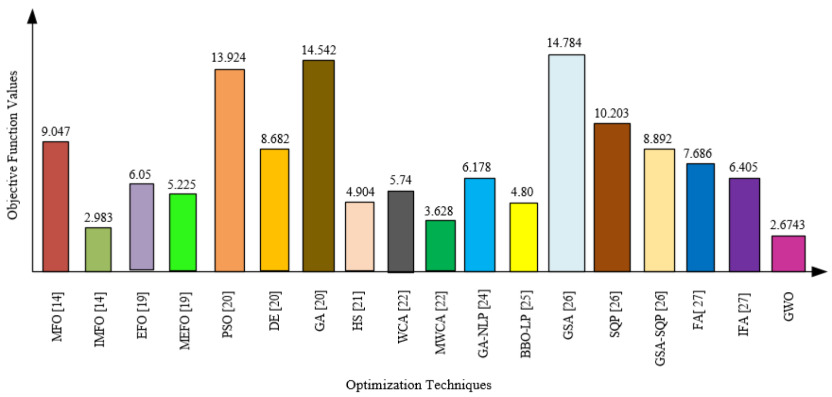

Fig. 13 Comparative analysis of the OF value with standard NI relay characteristics using different optimization techniques

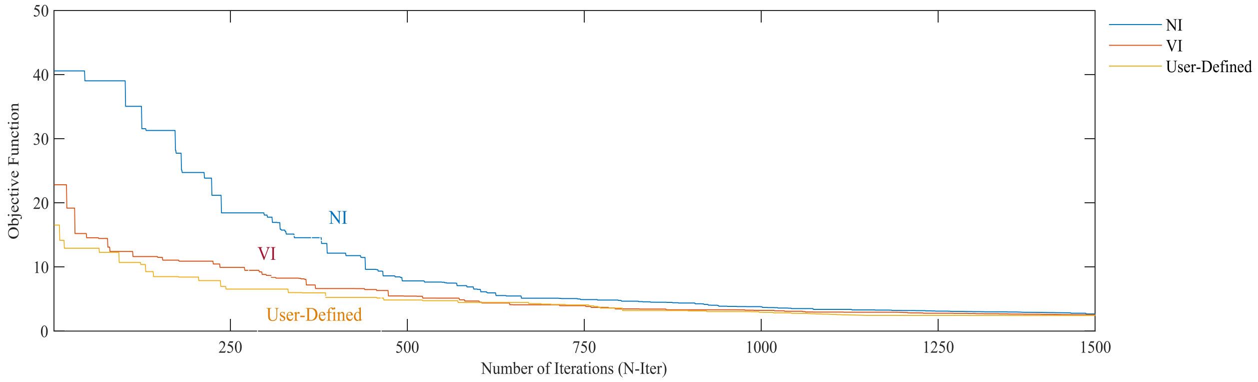

Fig. 14 Convergence plot of GWO with NI, VI, and user-defined relay characteristics in the 9-bus test system

3.3. 15-bus test system

The 15-bus-test system consists of twenty-one lines and six distributed generators (DG1-DG6), as shown in Fig. 15. Each line is protected by two DOCRs placed at both ends of the line, so the total number of DOCRs required to protect all the feeders is 42. All other components are assumed to have a self-fault control unit. An external grid (EG) of rating 200 MVA is connected to Bus8. All the generators (DG_1-DG_5) have the same rating of 15 MVA, 20 kV, and a synchronous reactance of 0.15. All the other test system details are taken from the work of Amraee [22].

The operating range of TMS and PS is considered in between [0.1-1.1] and [0.5-2.5], respectively. The value of CTI is taken as 0.2 s. The 15-bus test system consists of 82 PBRPs (RP1-RP82) for distinct fault locations (F1, F2, ……, F42), as shown in Table 6. The decision variables for conventional DOCR are selected as PS_1-PS_{42} and TMS_1-TMS_{42} for the relays R1-R42. For microprocessor-based relays, the decision variables are chosen as PS_1-PS_{42}, TMS_1-TMS_{42}, λ_1-λ_{42}, and γ_1-γ_{42}.

The optimal relay settings obtained by using the GWO algorithm for the 15-bus test system with standard (NI and VI) and user-defined relay characteristics are shown in Table 7. It can be observed that the total relay operating time is reduced as the relay characteristics change from NI to user-defined characteristics. The total relay operating time obtained with NI, VI, and user-defined relay characteristics is 16.5910 s, 4.9881 s, and 4.3603 s, respectively. The primary and backup relay operating time obtained with NI, VI, and user-defined relay characteristics is shown in Figs. 16-18, respectively.

The primary and backup relay operating time with respect to the corresponding RP is given in Appendix (Table C). From the results, it can be seen that for each relay pair (RP1-RP82), the operating time of the backup relay is more than the primary relay. The backup and primary relay operating time differences are always more than the considered value of CTI (0.2 s). This authenticates the proper relay coordination among all the DOCRs. The obtained results reveal that the total relay operating time obtained using the GWO algorithm with user-defined relay characteristics is the least compared to the other relay characteristics. Thus, the user-defined relay characteristic gives the best results than other standard relay characteristics while keeping the backup relay operating time within the acceptable limit.

The obtained OF values with NI relay characteristics by using the GWO algorithm and other existing optimization techniques such as MFO [14], EFO [19], DE [20], PSO [20], GA [20], HS [21], WCA [22], CSA [28], EBSA [29], D-JAYA [30] are shown in Fig. 19. Similarly, the obtained optimal OF value with user-defined relay characteristics using the GWO technique is 4.3603 s, which is less than the value obtained by IMFO [14].

The convergence plot of the GWO algorithm for the 15-bus test system with NI, VI, and user-defined relay characteristics is shown in Fig. 20. It can be seen that fewer iterations are required for user-defined relay characteristics when compared to the standard relay characteristics.

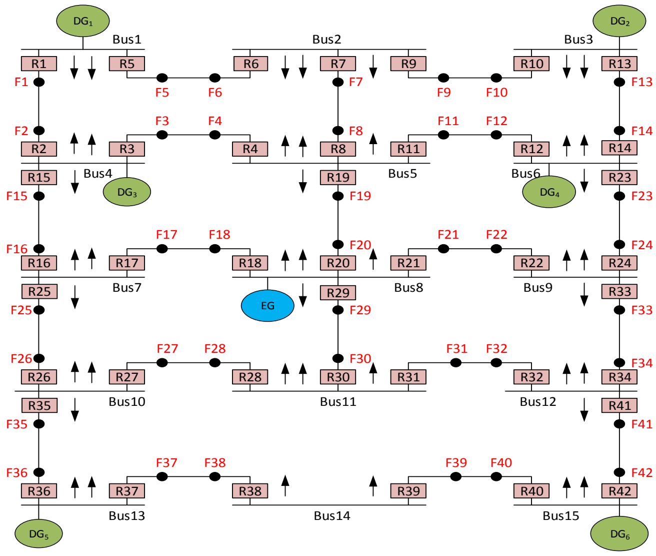

Fig. 15 The 15-bus test system

Table 6 PBRPs of the 15-bus test system

Fault point (F)	Relay pair (RP)	Primary relay	Backup relay	Fault point (F)	Relay pair (RP)	Primary relay	Backup relay
F1	RP1	R1	R6	F20	RP42	R20	R30
F2	RP2	R2	R4	F21	RP43	R21	R17
F2	RP3	R2	R16	F21	RP44	R21	R19
F3	RP4	R3	R1	F21	RP45	R21	R30
F3	RP5	R3	R16	F22	RP46	R22	R23
F4	RP6	R4	R7	F22	RP47	R22	R34
F4	RP7	R4	R12	F23	RP48	R23	R11
F4	RP8	R4	R20	F23	RP49	R23	R13
F5	RP9	R5	R2	F24	RP50	R24	R21
F6	RP10	R6	R8	F24	RP51	R24	R34
F6	RP11	R6	R10	F25	RP52	R25	R15
F7	RP12	R7	R5	F25	RP53	R25	R18
F7	RP13	R7	R10	F26	RP54	R26	R28
F8	RP14	R8	R3	F26	RP55	R26	R36
F8	RP15	R8	R12	F27	RP56	R27	R25
F8	RP16	R8	R20	F27	RP57	R27	R36
F9	RP17	R9	R5	F28	RP58	R28	R29
F9	RP18	R9	R8	F28	RP59	R28	R32
F10	RP19	R10	R14	F29	RP60	R29	R17
F11	RP20	R11	R3	F29	RP61	R29	R19
F11	RP21	R11	R7	F29	RP62	R29	R22
F11	RP22	R11	R20	F30	RP63	R30	R27
F12	RP23	R12	R13	F30	RP64	R30	R32
F12	RP24	R12	R24	F31	RP65	R31	R27
F13	RP25	R13	R9	F31	RP66	R31	R29
F14	RP26	R14	R11	F32	RP67	R32	R33
F14	RP27	R14	R24	F32	RP68	R32	R42
F15	RP28	R15	R1	F33	RP69	R33	R21
F15	RP29	R15	R4	F33	RP70	R33	R23
F16	RP30	R16	R18	F34	RP71	R34	R31
F16	RP31	R16	R26	F34	RP72	R34	R42
F17	RP32	R17	R15	F35	RP73	R35	R25
F17	RP33	R17	R26	F35	RP74	R35	R28
F18	RP34	R18	R19	F36	RP75	R36	R38
F18	RP35	R18	R22	F37	RP76	R37	R35
F18	RP36	R18	R30	F38	RP77	R38	R40
F19	RP37	R19	R3	F39	RP78	R39	R37
F19	RP38	R19	R7	F40	RP79	R40	R41
F19	RP39	R19	R12	F41	RP80	R41	R31
F20	RP40	R20	R17	F41	RP81	R41	R33
F20	RP41	R20	R22	F42	RP82	R42	R39

Table 7 Optimal settings of DOCRs with NI, VI, and user-defined relay characteristics obtained by using GWO

Relay	NI characteristics		VI characteristics		User-defined relay characteristics			
	TMS	PS	TMS	PS	TMS	PS	λ	γ
R1	0.2060	0.5055	0.1606	0.9993	0.4152	0.9056	17.6667	1.3310
R2	0.1174	1.3308	0.1621	0.8389	0.3916	0.7783	73.8544	1.7685
R3	0.2011	0.8080	0.3856	0.5079	0.1504	1.3687	37.3132	1.3938
R4	0.1738	0.7638	0.2339	0.5667	0.1703	1.0366	30.3513	1.3805
R5	0.1681	1.4517	0.2484	0.7612	0.1043	1.9849	49.2296	1.6807
R6	0.1445	1.7727	0.1845	1.1077	0.9607	1.7917	13.7752	1.9405
R7	0.2336	0.5752	0.1032	1.6488	0.1799	1.2604	23.7580	1.3473
R8	0.1331	1.4233	0.2887	0.5067	0.1715	0.8295	39.8637	1.3384
R9	0.1559	1.4952	0.1104	1.5422	0.1214	2.2916	13.9373	1.2158
R10	0.2209	0.6563	0.1018	1.5218	0.4415	1.4293	41.3769	1.8950
R11	0.1323	1.1177	0.2125	0.6095	0.3037	0.8371	49.0816	1.6304
R12	0.1000	1.9305	0.2462	0.5146	0.1586	1.4422	23.9175	1.4575
R13	0.1798	1.0020	0.1139	1.5410	0.5444	1.5613	22.4625	1.8384
R14	0.1444	1.0114	0.2743	0.5166	0.1349	0.8983	48.8826	1.3716
R15	0.1855	0.6632	0.1222	1.1278	0.2675	0.6218	37.7093	1.3390
R16	0.1942	0.6824	0.1151	1.1669	0.3845	2.2776	16.9291	1.9984
R17	0.1823	1.0683	0.1546	1.0781	0.2033	1.5134	30.6516	1.5131
R18	0.1716	0.7724	0.2927	0.6502	0.2803	1.5093	15.6529	1.3135
R19	0.2005	0.6469	0.1009	1.7318	0.1038	1.6839	47.7108	1.4537
R20	0.1592	0.8818	0.2635	0.6719	0.1140	1.8783	73.6932	1.7452
R21	0.1321	1.3332	0.1093	1.6644	0.6175	0.8299	16.3049	1.3379
R22	0.1899	0.7589	0.3696	0.5009	0.1206	0.8100	34.9268	1.1043
R23	0.1339	1.1775	0.2610	0.5646	0.5745	1.3409	13.5279	1.5983
R24	0.1916	0.5442	0.2090	0.7071	0.4145	1.0331	47.7480	1.8126
R25	0.2703	0.5091	0.2657	0.6713	0.3496	0.5822	22.2179	1.2508
R26	0.1523	1.4935	0.1815	0.8618	0.3443	0.9145	13.7680	1.2731
R27	0.2132	0.8265	0.1326	1.2936	0.1521	1.8181	51.8675	1.9722
R28	0.1804	1.6146	0.3318	0.7006	0.3383	1.3969	27.4168	1.6735
R29	0.1268	1.6771	0.1863	1.0600	0.2206	1.2987	27.0982	1.3649
R30	0.1939	0.7915	0.3545	0.5076	0.3737	2.0326	14.8316	1.7031
R31	0.2159	0.7403	0.2996	0.5863	0.2069	1.3698	22.9938	1.3553
R32	0.2220	0.6226	0.1194	1.0548	0.1643	1.3557	60.8943	1.8137
R33	0.2594	0.6750	0.1916	1.0498	0.1199	2.4157	30.0134	1.7399
R34	0.2099	1.0035	0.5299	0.5009	0.1126	1.4924	55.7727	1.4659
R35	0.2276	0.7048	0.1336	1.2558	0.2019	1.1337	47.8076	1.6750
R36	0.1342	1.7793	0.2751	0.5967	0.3100	0.5089	56.8110	1.3993
R37	0.2424	0.5637	0.3051	0.7617	0.5113	1.2875	19.9364	1.6593
R38	0.1543	1.7457	0.3632	0.6579	0.1474	1.0030	39.2112	1.2547
R39	0.1386	1.6445	0.2983	0.7772	0.1460	2.0211	65.1285	1.9991
R40	0.2730	0.5302	0.1011	1.9528	0.1109	0.9067	79.2216	1.4194
R41	0.1456	2.2666	0.1000	1.9251	0.1049	2.3225	19.5554	1.2955
R42	0.1000	2.0311	0.1497	0.9714	0.1847	1.1313	23.8209	1.3118
OF	16.5910 s		4.9881 s		4.3603 s			

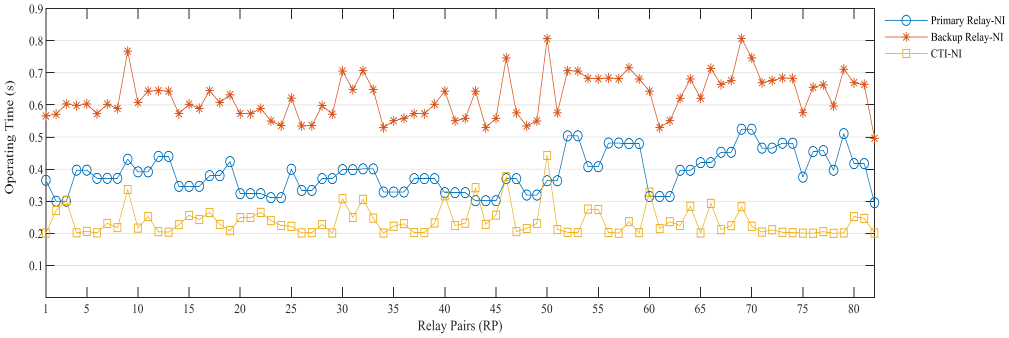

Fig. 16 Relay operating time with NI relay characteristics obtained by using GWO

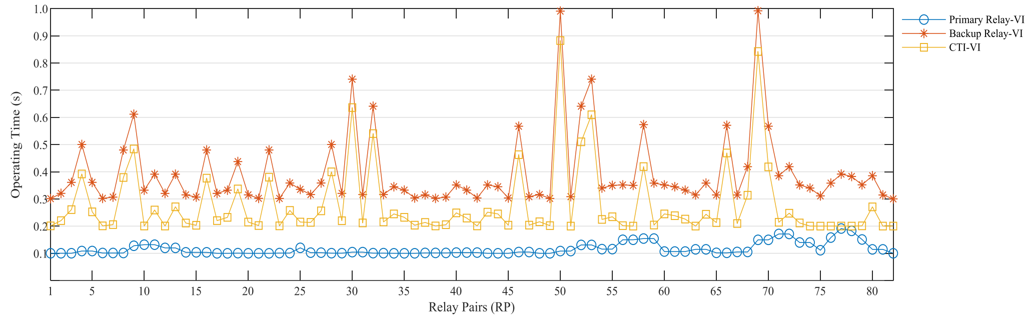

Fig. 17 Relay operating time with VI relay characteristics obtained by using GWO

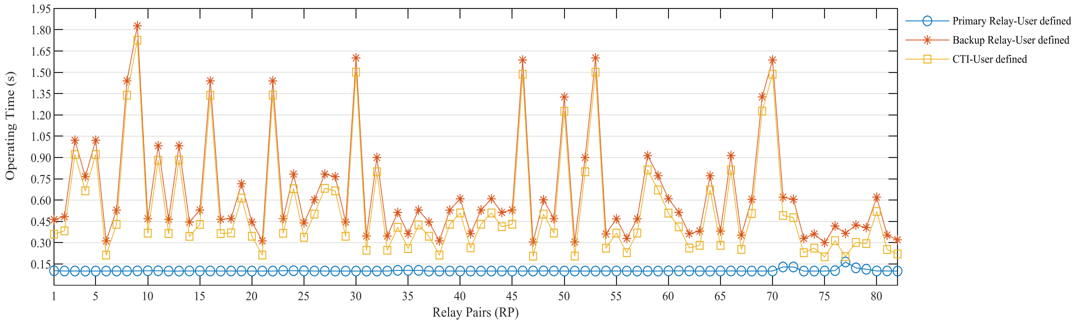

Fig. 18 Relay operating time with user-defined relay characteristics obtained by using GWO

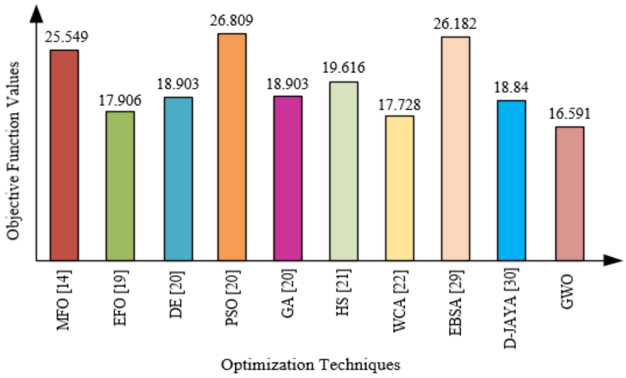

Fig. 19 Comparative analysis of the OF value with standard NI relay characteristics using different optimization techniques

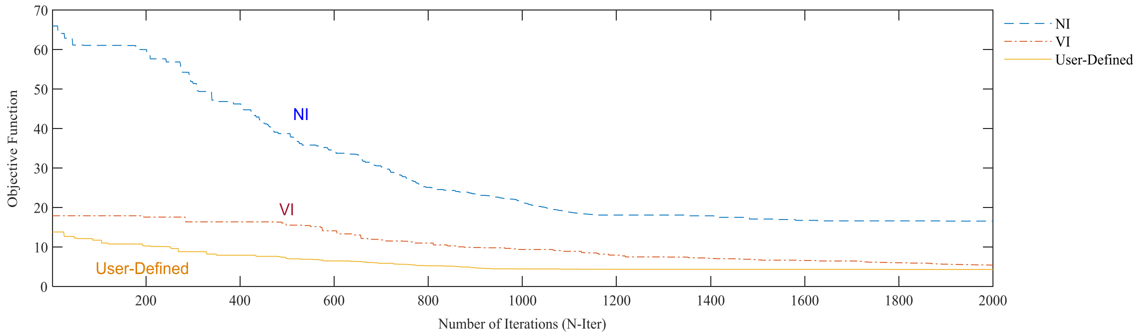

Fig. 20 Convergence plot of GWO with NI, VI, and user-defined relay characteristics in the 15- bus test system

3.4. Comparative analysis of obtained results

A comparative analysis of the total operating time of DOCRs obtained by GWO with NI, VI, and user-defined characteristics is presented in Table 8. From the results, it can be concluded that for the 8-bus test system, the percentage reduction in the total relay operating time for the VI and user-defined characteristics as compared to NI characteristics is 45.74% and 67.45%, respectively. Similarly, for the 9-bus and 15-bus test systems, the percentage reduction in the total relay operating time for the VI and user-defined relay characteristics as compared to NI relay characteristics is 4.58%, 9.15%, 69.93%, 73.71%, respectively. It can also be concluded that the DOCRs with user-defined characteristics achieve the highest reduction in the total relay operating time.

Table 8 Comparative analysis of total operating time with NI, VI, and user-defined relay characteristics using GWO

Test system	Total relay operating time (s)			Reduction with respect to NI	
	NI	VI	User-defined	VI	User-defined
8-bus	6.0313 s	3.2720 s	1.9627 s	45.74%	67.45%
9-bus	2.6743 s	2.5518 s	2.4296 s	4.58%	9.15%
15-bus	16.5910 s	4.9881 s	4.3603 s	69.93%	73.71%

4. Conclusions

This study uses the GWO algorithm to obtain optimal solutions for the overcurrent relay coordination problem with standard (NI and VI) and user-defined relay characteristics. The main advantage of the user-defined relay is that its characteristic can be adjusted to get the optimal values of the relay characteristic coefficients (λ and γ). The obtained results using the GWO algorithm indicate that the total relay operating time can be significantly reduced up to 67.45%, 9.15%, and 73.71% with the user-defined relay characteristics for the standard 8-bus, 9-bus, and 15-bus test systems, respectively. The involvement of non-linear constraints in OF using the penalty factor and discrete selection of PS variables for standard and user-defined relays may be considered the future scope for researchers.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Table A Relay operating time and MCT for the 8-bus test system

Relay pair	Primary relay	Backup relay	NI relay characteristics			VI relay characteristics			User-defined relay characteristics		
			$t_{i,k}$	$t_{j,k}$	MCT	$t_{i,k}$	$t_{j,k}$	MCT	$t_{i,k}$	$t_{j,k}$	MCT
RP1	R1	R6	0.2276	0.5303	0.3027	0.1288	0.4313	0.3025	0.1002	0.4052	0.3050
RP2	R2	R1	0.7073	1.0197	0.3124	0.3566	0.6681	0.3114	0.2319	0.9489	0.7170
RP3	R2	R7	0.7073	1.0120	0.3048	0.3566	0.6739	0.3173	0.2319	0.7682	0.5363
RP4	R3	R2	0.5502	0.8515	0.3013	0.3168	0.6190	0.3022	0.1997	0.5048	0.3051
RP5	R4	R3	0.3328	0.6333	0.3005	0.1988	0.4996	0.3008	0.1358	0.4370	0.3012
RP6	R5	R4	0.2199	0.5222	0.3023	0.1080	0.4088	0.3008	0.1003	0.4005	0.3002
RP7	R6	R5	0.4313	0.9242	0.4929	0.2076	0.5466	0.3390	0.1364	1.5280	1.3916
RP8	R6	R14	0.4313	0.9845	0.5533	0.2076	0.7440	0.5365	0.1364	0.7990	0.6626
RP9	R7	R5	0.5842	0.9242	0.3400	0.2165	0.5466	0.3301	0.1012	1.5280	1.4268
RP10	R7	R13	0.5842	1.1013	0.5171	0.2165	0.7438	0.5273	0.1012	1.2698	1.1686
RP11	R8	R7	0.3923	1.0120	0.6197	0.2144	0.6739	0.4595	0.1062	0.7682	0.6620
RP12	R8	R9	0.3923	1.1552	0.7629	0.2144	0.5583	0.3439	0.1062	1.7462	1.6400
RP13	R9	R10	0.2210	0.5219	0.3009	0.1272	0.4281	0.3009	0.1013	0.4049	0.3036
RP14	R10	R11	0.3347	0.6352	0.3004	0.2439	0.5444	0.3006	0.1452	0.4454	0.3002
RP15	R11	R12	0.5500	0.8999	0.3499	0.3539	0.6542	0.3002	0.1947	0.4959	0.3012
RP16	R12	R13	0.6827	1.1013	0.4186	0.4031	0.7438	0.3408	0.2069	1.2698	1.0629
RP17	R12	R14	0.6827	0.9845	0.3019	0.4031	0.7440	0.3410	0.2069	0.7990	0.5921
RP18	R13	R8	0.2401	0.5457	0.3056	0.1394	0.4450	0.3056	0.1001	0.4313	0.3312
RP19	R14	R1	0.5561	1.0197	0.4635	0.2568	0.6681	0.4112	0.1026	0.9489	0.8462
RP20	R14	R9	0.5561	1.1552	0.5991	0.2568	0.5583	0.3015	0.1026	1.7462	1.6436

Table B Relay operating time and MCT for the 9-bus test system

Relay pair	Primary relay	Backup relay	NI relay characteristics			VI relay characteristics			User-defined relay characteristics		
			$t_{i,k}$	$t_{j,k}$	MCT	$t_{i,k}$	$t_{j,k}$	MCT	$t_{i,k}$	$t_{j,k}$	MCT
RP1	R1	R15	0.1005	0.3012	0.2007	0.1003	0.4457	0.3453	0.1000	0.7042	0.6042
RP2	R1	R17	0.1005	0.3394	0.2389	0.1003	0.8153	0.7149	0.1000	1.8883	1.7883
RP3	R2	R4	0.1165	0.3167	0.2002	0.1002	0.3024	0.2022	0.1030	0.9928	0.8899
RP4	R3	R1	0.1239	0.3932	0.2692	0.1172	1.0536	0.9363	0.1025	0.4742	0.3717
RP5	R4	R6	0.1179	0.3966	0.2787	0.1000	0.6052	0.5052	0.1001	1.1670	1.0669
RP6	R5	R3	0.1666	0.3684	0.2018	0.1430	0.3511	0.2081	0.1026	0.3754	0.2728
RP7	R6	R8	0.1005	1.4205	1.3200	0.1004	0.5806	0.4803	0.1004	2.1895	2.0891
RP8	R6	R23	0.1005	0.5133	0.4128	0.1004	0.8384	0.7380	0.1004	1.1493	1.0489
RP9	R7	R5	0.1002	0.3004	0.2002	0.1004	0.3008	0.2004	0.1001	0.3037	0.2036
RP10	R7	R23	0.1002	0.5133	0.4132	0.1004	0.8384	0.7380	0.1001	1.1493	1.0492
RP11	R8	R10	0.1666	0.3667	0.2001	0.1699	0.3704	0.2005	0.1087	0.6586	0.5499
RP12	R9	R7	0.1207	0.3677	0.2470	0.1004	0.5184	0.4179	0.1016	0.4996	0.3980
RP13	R10	R12	0.1237	0.3690	0.2452	0.1087	0.5831	0.4744	0.1005	1.6533	1.5528
RP14	R11	R9	0.1161	0.3261	0.2099	0.1003	0.3550	0.2547	0.1008	0.4343	0.3335
RP15	R12	R14	0.1010	0.3793	0.2783	0.1001	0.4326	0.3326	0.1000	1.8377	1.7377
RP16	R12	R21	0.1010	0.7988	0.6979	0.1001	1.4698	1.3697	0.1000	1.1163	1.0163
RP17	R13	R11	0.1002	0.3058	0.2055	0.1000	0.3504	0.2504	0.1006	0.6386	0.5380
RP18	R14	R21	0.1006	0.7988	0.6982	0.1003	1.4698	1.3696	0.1004	1.1163	1.0159
RP19	R15	R13	0.1132	0.3808	0.2676	0.1007	0.6139	0.5132	0.1002	2.9219	2.8217
RP20	R15	R19	0.1132	0.3264	0.2132	0.1007	0.8343	0.7336	0.1002	1.0965	0.9963
RP21	R16	R2	0.1000	0.3103	0.2103	0.1069	0.3460	0.2392	0.1000	0.5241	0.4240
RP22	R16	R17	0.1000	0.3015	0.2015	0.1069	0.7163	0.6094	0.1000	1.4240	1.3240
RP23	R18	R2	0.1003	0.3103	0.2100	0.1009	0.3460	0.2452	0.1004	0.5241	0.4237
RP24	R18	R15	0.1003	0.3513	0.2510	0.1009	0.5235	0.4226	0.1004	0.8906	0.7903
RP25	R20	R13	0.1024	0.3808	0.2785	0.1001	0.6139	0.5138	0.1011	2.9219	2.8208
RP26	R20	R16	0.1024	0.3111	0.2088	0.1001	0.4700	0.3699	0.1011	0.9806	0.8795
RP27	R22	R11	0.1002	0.3058	0.2055	0.1007	0.3504	0.2497	0.1020	0.6386	0.5365
RP28	R22	R14	0.1002	0.3793	0.2790	0.1007	0.4326	0.3320	0.1020	1.8377	1.7357
RP29	R24	R5	0.1001	0.3004	0.2002	0.1000	0.3008	0.2008	0.1026	0.3037	0.2011
RP30	R24	R8	0.1001	0.3006	0.2004	0.1000	0.3007	0.2007	0.1026	0.3341	0.2315

Table C Relay operating time and MCT for the 15-bus test system

Relay pair	Primary relay	Backup relay	NI relay characteristics			VI relay characteristics			User-defined relay characteristics		
			$t_{i,k}$	$t_{j,k}$	MCT	$t_{i,k}$	$t_{j,k}$	MCT	$t_{i,k}$	$t_{j,k}$	MCT
RP1	R1	R6	0.3651	0.5657	0.2006	0.1002	0.3011	0.2010	0.1026	0.4625	0.3600
RP2	R2	R4	0.3000	0.5712	0.2711	0.1003	0.3205	0.2202	0.1006	0.4838	0.3832
RP3	R2	R16	0.3000	0.6030	0.3029	0.1003	0.3610	0.2607	0.1006	1.0213	0.9207
RP4	R3	R1	0.3967	0.5979	0.2011	0.1084	0.5003	0.3919	0.1001	0.7654	0.6652
RP5	R3	R16	0.3967	0.6030	0.2063	0.1084	0.3610	0.2526	0.1001	1.0213	0.9211
RP6	R4	R7	0.3713	0.5725	0.2012	0.1012	0.3022	0.2010	0.1005	0.3129	0.2124
RP7	R4	R12	0.3713	0.6023	0.2310	0.1012	0.3068	0.2056	0.1005	0.5296	0.4291
RP8	R4	R20	0.3713	0.5889	0.2176	0.1012	0.4801	0.3789	0.1005	1.4396	1.3391
RP9	R5	R2	0.4308	0.7673	0.3365	0.1278	0.6117	0.4839	0.1015	1.8278	1.7263
RP10	R6	R8	0.3912	0.6073	0.2161	0.1317	0.3323	0.2005	0.1022	0.4693	0.3671
RP11	R6	R10	0.3912	0.6431	0.2519	0.1317	0.3910	0.2593	0.1022	0.9827	0.8805
RP12	R7	R5	0.4396	0.6442	0.2046	0.1199	0.3203	0.2004	0.1001	0.4647	0.3645
RP13	R7	R10	0.4396	0.6431	0.2035	0.1199	0.3910	0.2711	0.1001	0.9827	0.8826
RP14	R8	R3	0.3463	0.5728	0.2265	0.1036	0.3150	0.2114	0.1010	0.4455	0.3446
RP15	R8	R12	0.3463	0.6023	0.2560	0.1036	0.3068	0.2031	0.1010	0.5296	0.4286
RP16	R8	R20	0.3463	0.5889	0.2426	0.1036	0.4801	0.3765	0.1010	1.4396	1.3386
RP17	R9	R5	0.3793	0.6442	0.2649	0.1000	0.3203	0.2203	0.1004	0.4647	0.3642
RP18	R9	R8	0.3793	0.6073	0.2280	0.1000	0.3323	0.2322	0.1004	0.4693	0.3689
RP19	R10	R14	0.4233	0.6314	0.2081	0.1007	0.4374	0.3368	0.1007	0.7152	0.6144
RP20	R11	R3	0.3235	0.5728	0.2493	0.1000	0.3150	0.2150	0.1001	0.4455	0.3455
RP21	R11	R7	0.3235	0.5725	0.2490	0.1000	0.3022	0.2022	0.1001	0.3129	0.2128
RP22	R11	R20	0.3235	0.5889	0.2654	0.1000	0.4801	0.3801	0.1001	1.4396	1.3395
RP23	R12	R13	0.3108	0.5500	0.2391	0.1009	0.3019	0.2010	0.1027	0.4691	0.3664
RP24	R12	R24	0.3108	0.5354	0.2246	0.1009	0.3586	0.2578	0.1027	0.7831	0.6804
RP25	R13	R9	0.3995	0.6214	0.2219	0.1202	0.3352	0.2150	0.1014	0.4392	0.3377
RP26	R14	R11	0.3334	0.5344	0.2010	0.1024	0.3162	0.2137	0.1004	0.6021	0.5017
RP27	R14	R24	0.3334	0.5354	0.2020	0.1024	0.3586	0.2562	0.1004	0.7831	0.6827
RP28	R15	R1	0.3705	0.5979	0.2274	0.1006	0.5003	0.3997	0.1001	0.7654	0.6652
RP29	R15	R4	0.3705	0.5712	0.2007	0.1006	0.3205	0.2199	0.1001	0.4453	0.3452
RP30	R16	R18	0.3982	0.7056	0.3073	0.1044	0.7405	0.6361	0.1001	1.6015	1.5014
RP31	R16	R26	0.3982	0.6478	0.2496	0.1044	0.3162	0.2118	0.1001	0.3468	0.2467
RP32	R17	R15	0.4006	0.7067	0.3061	0.1007	0.6411	0.5404	0.1003	0.8998	0.7995
RP33	R17	R26	0.4006	0.6478	0.2472	0.1007	0.3162	0.2155	0.1003	0.3468	0.2465
RP34	R18	R19	0.3285	0.5293	0.2008	0.1000	0.3450	0.2449	0.1051	0.5132	0.4081
RP35	R18	R22	0.3285	0.5506	0.2221	0.1000	0.3324	0.2323	0.1051	0.3638	0.2587
RP36	R18	R30	0.3285	0.5580	0.2295	0.1000	0.3036	0.2035	0.1051	0.5300	0.4249
RP37	R19	R3	0.3703	0.5728	0.2025	0.1015	0.3150	0.2136	0.1002	0.4455	0.3454
RP38	R19	R7	0.3703	0.5725	0.2022	0.1015	0.3022	0.2007	0.1002	0.3129	0.2127
RP39	R19	R12	0.3703	0.6023	0.2320	0.1015	0.3068	0.2053	0.1002	0.5296	0.4294
RP40	R20	R17	0.3265	0.6430	0.3165	0.1027	0.3515	0.2488	0.1001	0.6096	0.5096
RP41	R20	R22	0.3265	0.5506	0.2241	0.1027	0.3324	0.2297	0.1001	0.3638	0.2638
RP42	R20	R30	0.3265	0.5580	0.2315	0.1027	0.3036	0.2008	0.1001	0.5300	0.4299
RP43	R21	R17	0.3013	0.6430	0.3417	0.1001	0.3515	0.2514	0.1003	0.6096	0.5093
RP44	R21	R19	0.3013	0.5293	0.2279	0.1001	0.3450	0.2449	0.1003	0.5132	0.4128
RP45	R21	R30	0.3013	0.5580	0.2567	0.1001	0.3036	0.2035	0.1003	0.5300	0.4297
RP46	R22	R23	0.3700	0.7464	0.3764	0.1047	0.5675	0.4628	0.1005	1.5868	1.4863
RP47	R22	R34	0.3700	0.5752	0.2052	0.1047	0.3084	0.2037	0.1005	0.3056	0.2051
RP48	R23	R11	0.3191	0.5344	0.2154	0.1000	0.3162	0.2161	0.1011	0.6021	0.5010
RP49	R23	R13	0.3191	0.5500	0.2309	0.1000	0.3019	0.2018	0.1011	0.4691	0.3680
RP50	R24	R21	0.3635	0.8063	0.4428	0.1083	0.9908	0.8826	0.1002	1.3257	1.2254
RP51	R24	R34	0.3635	0.5752	0.2117	0.1083	0.3084	0.2001	0.1002	0.3056	0.2054
RP52	R25	R15	0.5035	0.7067	0.2032	0.1309	0.6411	0.5102	0.1001	0.8998	0.7996
RP53	R25	R18	0.5035	0.7056	0.2021	0.1309	0.7405	0.6096	0.1001	1.6015	1.5013
RP54	R26	R28	0.4072	0.6826	0.2754	0.1154	0.3400	0.2246	0.1007	0.3617	0.2611
RP55	R26	R36	0.4072	0.6816	0.2743	0.1154	0.3499	0.2345	0.1007	0.4680	0.3673
RP56	R27	R25	0.4812	0.6839	0.2027	0.1498	0.3516	0.2018	0.1002	0.3301	0.2299
RP57	R27	R36	0.4812	0.6816	0.2004	0.1498	0.3499	0.2001	0.1002	0.4680	0.3678
RP58	R28	R29	0.4794	0.7156	0.2363	0.1543	0.5733	0.4190	0.1002	0.9132	0.8131
RP59	R28	R32	0.4794	0.6809	0.2016	0.1543	0.3583	0.2040	0.1002	0.7717	0.6715
RP60	R29	R17	0.3147	0.6430	0.3284	0.1066	0.3515	0.2449	0.1013	0.6096	0.5083
RP61	R29	R19	0.3147	0.5293	0.2146	0.1066	0.3450	0.2384	0.1013	0.5132	0.4118
RP62	R29	R22	0.3147	0.5506	0.2359	0.1066	0.3324	0.2258	0.1013	0.3638	0.2625
RP63	R30	R27	0.3965	0.6208	0.2243	0.1146	0.3148	0.2002	0.1000	0.3817	0.2817
RP64	R30	R32	0.3965	0.6809	0.2844	0.1146	0.3583	0.2437	0.1000	0.7717	0.6717
RP65	R31	R27	0.4201	0.6208	0.2007	0.1018	0.3148	0.2130	0.1009	0.3817	0.2808
RP66	R31	R29	0.4201	0.7136	0.2935	0.1018	0.5709	0.4691	0.1009	0.9132	0.8123
RP67	R32	R33	0.4526	0.6638	0.2113	0.1050	0.3146	0.2096	0.1003	0.3531	0.2528
RP68	R32	R42	0.4526	0.6761	0.2235	0.1050	0.4187	0.3137	0.1003	0.6055	0.5052
RP69	R33	R21	0.5244	0.8069	0.2825	0.1496	0.9920	0.8424	0.1004	1.3271	1.2268
RP70	R33	R23	0.5244	0.7464	0.2220	0.1496	0.5675	0.4179	0.1004	1.5868	1.4864
RP71	R34	R31	0.4654	0.6692	0.2038	0.1712	0.3854	0.2141	0.1290	0.6206	0.4916
RP72	R34	R42	0.4654	0.6761	0.2106	0.1712	0.4187	0.2475	0.1290	0.6055	0.4765
RP73	R35	R25	0.4807	0.6839	0.2032	0.1399	0.3516	0.2117	0.1001	0.3301	0.2300
RP74	R35	R28	0.4807	0.6826	0.2020	0.1399	0.3400	0.2002	0.1001	0.3617	0.2617
RP75	R36	R38	0.3749	0.5755	0.2005	0.1113	0.3113	0.2000	0.1004	0.3006	0.2002
RP76	R37	R35	0.4546	0.6549	0.2003	0.1579	0.3581	0.2002	0.1032	0.4176	0.3144
RP77	R38	R40	0.4575	0.6624	0.2049	0.1912	0.3915	0.2003	0.1641	0.3657	0.2016
RP78	R39	R37	0.3966	0.5966	0.2001	0.1826	0.3827	0.2001	0.1227	0.4246	0.3019
RP79	R40	R41	0.5103	0.7113	0.2009	0.1509	0.3519	0.2011	0.1132	0.4067	0.2935
RP80	R41	R31	0.4171	0.6692	0.2521	0.1145	0.3854	0.2709	0.1010	0.6206	0.5197
RP81	R41	R33	0.4171	0.6638	0.2467	0.1145	0.3146	0.2002	0.1010	0.3531	0.2521
RP82	R42	R39	0.2953	0.4961	0.2008	0.1001	0.3003	0.2002	0.1000	0.3205	0.2205