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APPLICATION KHA FOR OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS IN THE PRESENCE MULTI GCSC

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Abstract: Optimal coordination of direction overcurrent relays in the power systems in the presence of GTO Controlled Series Capacitor (GCSC) installed on meshed power system is studied in this paper. The coordination problem is formulated as a non-linear constrained mono-objective optimization problem. The objective function of this optimization problem is the minimization of the operation time of the associated relays in the systems, and the decision variables are: the time dial setting and the pickup current setting of each overcurrent relay. To solve this complex non linear optimization problem, a variant of evolutionary optimization algorithms named Krill Herd Algorithm (KHA) is used. The proposed algorithm is validated on IEEE 14-bus transmission network test system considering various scenarios. The obtained results show a high efficiency of the proposed method to solve such complex optimization problem, in such a way the relays coordination is guaranteed for all simulation scenarios with minimum operating time for each relays. The results of objective function are compared to other optimization algorithms.
Keywords: Meshed Power System, GTO Controlled Series Capacitor, Overcurrent Relay, Coordination Time, Krill Herd Algorithm

INTRODUCTION

System protection is an important part in the power network systems. The most important part in designing the protection needs to consider such as the type of relays, the size of circuit breaker and fuse, the type and size of current transformer, the coordination of relays, and them component to maintain the stability of the system. Then to maintain the stability each relay in the power network must setting in proper technique in term of current and time operation. During the operation of modern interconnected power systems, abnormal conditions can frequently occur. Such conditions cause interruption of the supply, and may damage the equipments connected to the system, arising the importance of designing a reliable protective system. In order to achieve such reliability, a back-up protective scheme is provided to act as a second line of defense in case of any failure in the primary protection. In other words, it should operate after a certain time delay known as Coordination Tine Interval (CTI), giving the chance for the primary protection to operate.

The fore mentioned situation leads to the formulation of the well-known protective relay setting coordination, that consists of the selection of a suitable setting of each relay such that their fundamental protective function is met under the desirable qualities of protective relaying, namely sensitivity, selectivity, reliability, and speed [1]. Overcurrent relaying, which is simple and economic, is commonly used for providing primary protection and as backup protection on power systems [2]. To reduce the power outages, mal-operation of the backup relays should be avoided, and therefore, Overcurrent relay coordination in power transmission and distribution networks is a major concern of protection engineer. A relay must get sufficient chance to protect the zone under its primary protection. Only if the primary protection does not clear the fault, the back-up protection should initiate tripping. Each protection relay in the power system needs to be coordinated with the relays protecting the adjacent equipment [3], the overall protection coordination is thus very complicated. Overcurrent relay have two types of settings: pickup current and dial time settings.

Recently, it is noticeable that the power demand has been increasing substantially worldwide. On the other hand, the expansion of power generation and transmission facilities and equipment has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC Transmission Current (FACTS) controllers offer many benefits to the network and have been mainly used for solving various power system steady state control problems [4, 5].

In recent years, many research efforts have been made to achieve optimum protection coordination (optimum solution for relay settings) without GCSC on power system using different optimization techniques, including Random Search (RS) technique is reported in [6], Evolutionary Algorithms (EA) is presented in [7] while Differential Evolution Algorithm (DEA) in [8], Modified Differential Evolution Algorithm (MDEA) in [9], and Self-Adaptive Differential Evolutionary (SADE) algorithm in [10], application Particle Swarm Optimization (PSO) in [11], and Modified Particle Swarm Optimizer in [12, 13], and Evolutionary Particle Swarm Optimization (EPSO)

Algorithm in [14], Box-Muller Harmony Search (BMHS) in [15], Zero-one Integer Programming (ZOIP) Approach in [16], Seeker Algorithm (SA) is presented in [17], and Teaching Learning-Based Optimization (TLBO) in [18].

This paper presents the solution of the coordination problem of IDMT directional overcurrent relays on meshed power system using KHA approach. The problem is formulated as a non linear constrained mono-objective optimization problem. Our goal behind this optimization is to find an optimal setting of Time Dial Setting (TDS) and Pickup current (I_P) of each relay that minimizes the operating time (T) of overall relays. The new idea presented in this paper, is taking into account the variation of the effective impedance of the line caused by the action of GCSC devices of the transmissions line. Two simulation scenarios with and without multi GCSCs are considered in this paper.

APPARENT RECTANCE INJECTED BY GCSC

The GCSC presented in thefigure1.a is the first that appearsin the family of seriescompensators. It consists ofacapacitance (C)connected in serieswith the transmission line andcontrolled by avalve-type GTOthyristorsmounted in anti-paralleland controlled byafiring angle (γ) variedbetween 0° and180° [19-22].

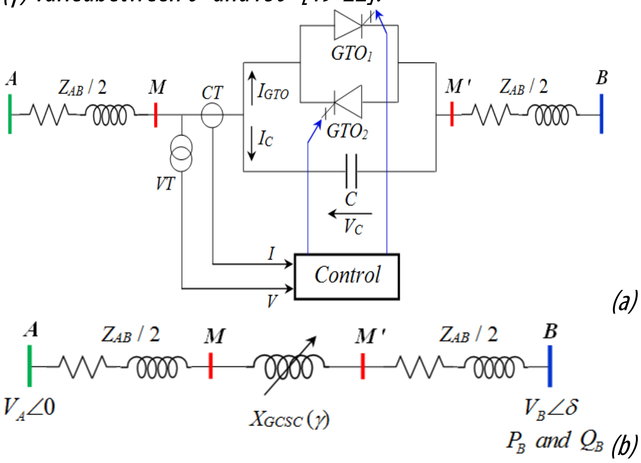

***Figure 1**. Transmission line in the presence of GCSC device. a). Control principle, b). Apparent reactance.*

Thiscompensator is installed in the transmission line AB between bus-bars A (source) and B (load) and modeled as a variablecapacitive reactance(X_{GCSC}). From figure1.b, this capacitive reactance is definedby the equation [21, 22]:

$$X_{GCSC}(\gamma) = X_{C.Max}\left[1 - \frac{2}{\pi}\gamma - \frac{1}{\pi}\sin(2\pi)\right] \quad (1)$$

where,

$$X_{C.Max} = 1/C_{GCSC}.\omega \quad (2)$$

The conduction angle (β) which varies between 0 to 90°, is defined by next relation:

$$\beta = \pi - 2\gamma = 2\left(\frac{\pi}{2} - \gamma\right) \quad (3)$$

From equation (3), the equation (2) becomes:

$$X_{GCSC}(\beta) = X_{C.Max}\left[1 - \left(\frac{\pi-\beta}{\pi}\right) - \frac{1}{\pi}\sin\left(\pi(\pi-\beta)\right)\right] \quad (4)$$

The relation of injected voltage is calculated by flowing equation:

$$V_{GCSC}(\beta) = V_{Max}\left[1 - \left(\frac{\pi-\beta}{\pi}\right) - \frac{1}{\pi}\sin\left(\pi(\pi-\beta)\right)\right] \quad (5)$$

Where, $V_{Max}$is maximum voltage injected and controlled by GCSC. The total transmission line ($Z_{AB-GCSC}$) impedance with GCSC inserted on midline is given by:

$$Z_{AB-GCSC} = R_{AB} + j\left[X_{AB} - X_{GCSC}(\beta)\right] \quad (6)$$

In the presence three phase fault, the fault current (I_F) is defined by [22]:

$$I_F = \frac{3.(V_A + V_{GCSC})}{Z_{AB.1} + X_{GCSC.1}} \quad (7)$$

Where, $Z_{AB.1}$and $X_{GCSC.1}$is positive component of line impedance compensated and GCSC respectively. From equation (7), the fault current is only related to parameters of transmission line and parameters of GCSC installed (V_{GCSC} and X_{GCSC}).

PROBLEM FORMULATION AND CONSTRAINTS

The coordination of directional overcurrent relays in a multi-loop system is formulated as an optimization problem. The coordination problem, including objective function and constraints, should satisfy three requirements.

Objective Function

The aim of this function (f) is to minimize the total operating time of all overcurrent protection relays in the system with respect to the coordination time constraint between the backup and primary relays.

$$f = Min\left\{\sum_{i=1}^{N} T_i\right\} \quad (8)$$

Where, T_i represents the operating time of the i^{th} relay, N represents the number of relays in the power system. For each protective relay the operating time T is defined by [9-11]:

$$T_i = TDS \times \frac{\alpha}{\left(I_M/I_P\right)^{\beta} + \gamma} \quad (9)$$

Where, T is relay operating time (sec), TDS is time dial setting (sec), I_M is the fault current measured by relay (A), I_P is pickup current (A). The constant α, β, and γ depend on the characteristic curve for IDMT directional overcurrent relay. The current I_M is defined by:

$$I_M = \frac{I_F}{K_{CT}} \quad (10)$$

where, I_F is the fault current, and K_{CT} is ratio of the current transformer.

Constraints

The coordination problem has two types of constraints, including the constraints of the relay characteristic and coordination constraints. Relay constraints include limits of relay operating time and settings. Coordination constraints are related to the coordination of primary and backup relays.

The operating time of a relay is a function of the pickup current setting and the fault current seen by the relay. Based on the type of relay, the operating time is determined via standard characteristic curves or analytic formula. The bounds on operating time are expressed by:

$$T_i^{\min} \le T_i \le T_i^{\max} \quad (11)$$

Where, $T_i^{\min}$ and $T_i^{\max}$ are the minimum and maximum operating times of the i^{th} overcurrent relay.

During the optimization procedure, the coordination between the primary and the backup relays must be verified. In this paper, the chronometric coordination between the primary and the backup relays is used as follows equation:

$$T_{backup} - T_{primary} \ge CTI \quad (12)$$

Where, T_{backup} and $T_{primary}$ are the operating time of the backup relay and the primary relay respectively, CTI is the coordination time interval.

The time dial setting (TDS) adjusts the time delay before the relay operates when the fault current reaches a value equal to, or greater than, the pickup current (I_P) setting [6-12].

$$TDS_i^{\min} \le TDS_i \le TDS_i^{\max} \quad (13)$$

$$I_{Pi}^{\min} \le I_{Pi} \le I_{Pi}^{\max} \quad (14)$$

where, $TDS_i^{\min}$ and $TDS_i^{\max}$ are the minimum and the maximum limits of TDS for the i^{th} relay. $I_{Pi}^{\min}$ and $I_{Pi}^{\max}$ are the minimum and the maximum limits of I_P for the i^{th} relay.

KRILL HERD ALGORITHM (KHA)

KHA is a recently developed heuristic algorithm based on the herding behavior of krill individuals. It has been first proposed by Gandomi and Alavi in 2012 [22-24]. It is a population based method consisting of a large number of krill in which each krill moves through a multi-dimensional search space to look for food. In this algorithm, the positions of krill individuals are considered as different design variables and the distance of the food from the krill individual is analogous to the fitness value of the objective function. In KHA, the individual krill alters its position and moves to the better positions.

Induction

In this process, the velocity of each krill is influenced by the movement of other krill individuals of the multi-dimensional search space and its velocity is dynamically adjusted by the local, target and repulsive vector. The velocity of the i^{th} krill at the m^{th} movements may be formulated as follows [22]:

$$V_i^m = \alpha_i V_i^{\max} + \omega_n V_i^{m-1} \quad (15)$$

and,

$$\alpha_i = \sum_{j=1}^{N_S} \left[\frac{f_i - f_j}{f_w - f_b} \times \frac{Z_i - Z_j}{|Z_i - Z_j| + rand(0,1)} \right] + 2\left[rand(0,1) + \frac{i}{i_{\max}} \right] f_i^{best} X_i^{best} \quad (16)$$

where, V_i^{max} is the maximum induced motion: V_i^m, V_i^{m-1} are the induced motion of the i^{th} krill at the m^{th} and $(m-1)^{th}$ movement; ω_n is the inertia weight of the motion induced: f_w and f_b are the worst and the best position respectively, among all krill individuals, of the population; f_i, f_j are the fitness value of the i^{th} and j^{th} individuals respectively. N_S is the number of krill individuals surrounding the particular krill; i, i_{max} are the current iteration and the maximum iteration number.

A sensing distance (SD_i) parameter is used to identify the neighboring members of each krill individual. The sensing distance may be represented by [23]:

$$SD_i = \frac{1}{5n_p} \sum_{k=1}^{n_p} |Z_i - Z_k| \quad (17)$$

where, n_p is the population size, Z_i and Z_k are the position of the i^{th} and K^{th} krill respectively.

Foraging Action

The foraging velocity of the i^{th} krill at the m^{th} movement may be expressed by [22]:

$$V_{f_i}^m = 0.02 \left[2\left(1 - \frac{i}{i_{\max}}\right) f_i \frac{\sum_{k=1}^{N_S} \frac{Z_k}{f_k}}{\sum_{k=1}^{N_S} \frac{1}{f_j}} + f_i^{best} X_i^{best} \right] + \omega_x V_{f_i}^{m-1} \quad (18)$$

where, ω_x is the inertia weight of the foraging motion, V_{fi}^{m-1}, V_{fi}^m, are the foraging motion of the i^{th} krill at the $(m - 1)^{th}$ and m movement.

Random Diffusion

The diffusion speed of krill individuals may be expressed as follows [22]:

$$V_{D_i}^m = \mu V_D^{\max} \quad (19)$$

where, V_D^{max} is the maximum diffusion speed; μ is a directional vector uniformly.

Position Update

In KHA, the krill individuals fly around in the multi-dimensional space and each krill adjusts its position based on induction motion, foraging motion and diffusion motion. The updated position of the i^{th} krill may be expressed as [24]:

$$Z_i^{m+1} = Z_i^m + \left(V_i^m + V_{fi}^m + V_{Di}^m\right) Pt \sum_{j=1}^{N_d} \left(u_j - l_j\right) \quad (20)$$

where, N_d is the number of control variables u_j, l_j are the maximum and minimum limits of the j^{th} control variable; P_t is the position constant factor.

Crossover

Depending upon the crossover probability, each krill individual interacts with others to update its position. The j^{th} components of the i^{th} krill may be updated by [22-24]:

$$Z_{i,j} = \begin{cases} Z_{k,j} & \text{if, } rand \le C_{R_i} \\ Z_{i,j} & \text{if, } rand > C_{R_i} \end{cases} \quad \text{where, } k = 1, 2, \ldots n_p;\ k \ne 1 \quad (21)$$

where, C_{Ri} is the crossover probability and is given by [22]:

$$C_{R_i} = 0.2 f_i^{best} \quad (22)$$

Mutation

In this process [24], a scalar number F_R scales the difference of tworandomly selected vectors $Z_{m,j}$ and $Z_{n,j}$ and the scaled difference is added to the best vector $Z_{best,j}$ whence the mutant vectors $Z_{i,j}^m$ is obtained.

$$Z_{i,j} = Z_{best,j} + F_R\left(Z_{m,j} - Z_{n,j}\right) \quad (23)$$

Using mutation probability (M_R) the modified value, $Z_{i,j}^{mod}$ is selected from $Z_{i,j}^{m}$ and $Z_{i,j}$ and it may mathematically expressed as [22, 24]:

$$Z_{i,j}^{\mathrm{mod}} = \begin{cases} Z_{i,j}^{m} & \text{if } rand \le M_R \\ Z_{i,j} & \text{if } rand > M_R \end{cases} \quad (24)$$

The proposed optimization algorithm includes steps below:

Step no. 1: Structure definition of data, the limit of scope and parameters,
Step no. 2: Definition of initial population,
Step no. 3: Calculation of the propriety of each Krill according to its location in the search environment,
Step no. 4: Calculation of the movement of each Krill,
Step no. 5: Induced movement of other Krill,
Step no. 6: Movement towards food,
Step no. 7: Physical diffusion based on chaotic portrait,
Step no. 8: Implementation of genetic operators,
Step no. 9: The update process of each krill in the search environment,
Step no. 10: Repetition of step no. 3 to 6 up to the desired accuracy,
Step no. 11: End.

CASE STUDY AND RESULTS

The impact of GCSC on directional relays coordination is performed on the following two scenarios: without and with multi GCSC installed at IEEE 14 bus transmission power systems. As we mentioned above, the relays coordination problem is formulated as constrained mono-objective problem and solved using the KHA optimization algorithm considering 82 decision variables (42 variables represent the I_P and 42 variables represent the TDS).

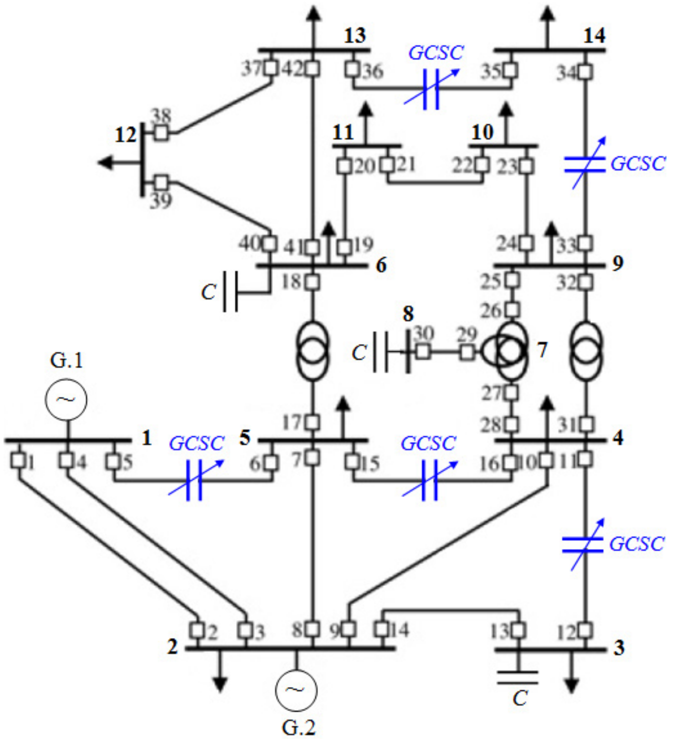

***Figure 2.** IEEE 14-bus power system with multi GCSC*

Figure 2, represents the case study of a network fed by 02 generators and with 14 buses, 20 transmission lines. The power system consists of 42 directional overcurrent relays. The power system study is compensated with five GCSCs located at middle of the transmission lines (1-5, 3-4, 4-5, 9-14, and 13-14), where conduction angle (β) varied between 5°, 45°, and 90° for all installed GCSCs on power system.

Impact of GCSC on CTI

Table 1 presents, the CTI values of the overcurrent relays without and with multi GCSC on three compensation degree.

***Table 1.** Impact of multi GCSC on CTI value*

Primary relay	Backup relay	Without GCSC	With GCSC		
			$\beta = 5°$	$\beta = 45°$	$\beta = 90°$
5	6	0.3400	-0.1124	-1.2366	-0.2507
11	12	0.3600	-0.1462	-1.6086	-0.7261
15	16	0.3200	-0.1123	-1.2352	-0.2504
33	34	0.3893	-0.0778	-0.8553	-0.4734
35	36	0.3321	-0.1061	-1.1666	-0.2365

From this table, it is clear that all relays are coordinated in the case without multi GCSC (superior reference value 0.3 sec), but among of them are not coordinated in the presence multi GCSC for all angle β (CTI value written in bold). Thus, we can conclude that GCSC causes a loss of coordination between the relays protection line. In this situation, we must compute the new settings of the relays to ensure the coordination.

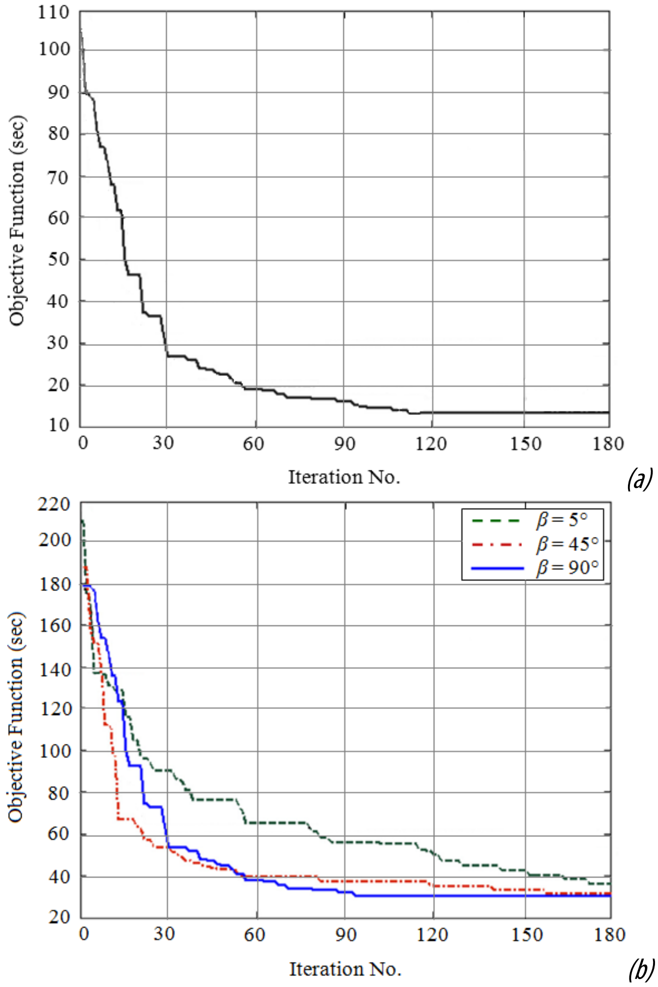

***Figure 3**: Convergence characteristics of KHA for all cases.*
a). Without GCSC, b). With GCSC.

Optimal Settings and Coordination

The optimization constraints for case all study in absence or presence multi GCSCs are:

- ✓ *CTI = 0.3 sec,*
- ✓ $50 \le I_{Pi} \le 1700$ *(A),*
- ✓ $0.02 \le TDS_i \le 0.30$ *(sec),*
- ✓ $0.05 \le T_i \le 1.50$ *(sec),*
- ✓ *Type of curve: very inverse.*

The KHA parameters are:

- ✓ $V_i^{max} = 0.01$,
- ✓ $V_D^{max} = 0.15$,
- ✓ $P_t = 0.20$,
- ✓ $\omega_n = 0.90$,
- ✓ $\omega_x = 0.90$,
- ✓ $G_{max} = 180$.

The convergence characteristics of the KHA without and with multi GCSCs are depicted in Figures 3.a and 3.b respectively.

From Figure 4.a, we can see that the optimization algorithm proposed is convergence within 120 iterations, and the value of objective function is 14.5384 sec. From Figure 4.b, the value of objective function in the presence multi GCSC is 16.4321 sec, 17.0347, and 19.3246 with conduction angle β equal 90°, 45° and 5 ° respectively. The optimal settings relay (I_P and TDS) for all cases are represented in Tables 2 and 3.

Table 2: *Optimal relays settings without GCSC*

Relay No.	I_P (A)	TDS (sec)	Relay No.	I_P (A)	TDS (sec)
1	876	0.031	22	526	0.180
2	368	0.042	23	175	0.196
3	368	0.046	24	701	0.226
4	876	0.031	25	421	0.127
5	548	0.072	26	1314	0.143
6	245	0.035	27	245	0.021
7	245	0.053	28	350	0.152
8	329	0.121	29	175	0.044
9	350	0.113	30	788	0.086
10	140	0.099	31	131	0.170
11	350	0.072	32	70	0.046
12	105	0.227	33	701	0.129
13	245	0.064	34	175	0.226
13	548	0.081	35	280	0.131
15	438	0.129	36	526	0.168
16	245	0.168	37	131	0.158
17	394	0.128	38	280	0.136
18	210	0.022	39	105	0.060
19	701	0.193	40	767	0.121
20	280	0.175	41	876	0.162
21	350	0.201	42	280	0.105

Table 3: *Optimal relays settings with multi GCSC*
a). β = 5°, b). β = 45°, c). β = 90°.

(a)

Relay No.	I_P (A)	TDS (sec)	Relay No.	I_P (A)	TDS (sec)
1	1011	0.036	22	607	0.208
2	425	0.048	23	202	0.227
3	425	0.048	24	809	0.260
4	1011	0.036	25	485	0.147
5	632	0.083	26	1517	0.165
6	283	0.041	27	283	0.022
7	283	0.061	28	404	0.175
8	379	0.140	29	202	0.051
9	404	0.131	30	910	0.100
10	162	0.114	31	152	0.196
11	404	0.083	32	81	0.053
12	121	0.262	33	809	0.148
13	283	0.074	34	202	0.261
13	632	0.094	35	324	0.151
15	506	0.149	36	607	0.193
16	283	0.194	37	152	0.182
17	455	0.148	38	324	0.157
18	243	0.025	39	121	0.069
19	809	0.223	40	885	0.140
20	324	0.202	41	1011	0.187
21	404	0.232	42	324	0.121

(b)

Relay No.	I_P (A)	TDS (sec)	Relay No.	I_P (A)	TDS (sec)
1	974	0.034	22	584	0.201
2	409	0.047	23	195	0.218
3	409	0.049	24	779	0.251
4	974	0.034	25	468	0.141
5	609	0.080	26	1461	0.159
6	273	0.039	27	273	0.021
7	273	0.058	28	390	0.169
8	365	0.135	29	195	0.049
9	390	0.126	30	877	0.096
10	156	0.110	31	146	0.189
11	390	0.080	32	78	0.051
12	117	0.253	33	779	0.143
13	273	0.071	34	195	0.252
13	609	0.090	35	312	0.145
15	487	0.143	36	584	0.186
16	273	0.186	37	146	0.176
17	438	0.142	38	312	0.152
18	234	0.024	39	117	0.066
19	779	0.215	40	852	0.135
20	312	0.194	41	974	0.181
21	390	0.223	42	312	0.116

(c)

Relay No.	I_P (A)	TDS (sec)	Relay No.	I_P (A)	TDS (sec)
1	859	0.030	22	515	0.177
2	361	0.041	23	172	0.192
3	361	0.044	24	687	0.221
4	859	0.030	25	412	0.125
5	537	0.071	26	1288	0.140
6	240	0.035	27	240	0.020
7	240	0.052	28	343	0.149
8	322	0.119	29	172	0.043
9	343	0.111	30	773	0.085
10	137	0.097	31	129	0.166
11	343	0.070	32	69	0.045
12	103	0.223	33	687	0.126
13	240	0.063	34	172	0.222
13	537	0.080	35	275	0.128
15	429	0.126	36	515	0.164
16	240	0.164	37	129	0.155
17	386	0.125	38	275	0.134
18	206	0.023	39	103	0.058
19	687	0.189	40	751	0.119
20	275	0.171	41	859	0.159
21	343	0.197	42	275	0.103

The new optimal value for coordination between primary and backup relays in the presence multi GCSC is presented in Table 4. After this table that all directional overcurrent relays are well coordinated (superior reference value equal 0.3 sec) after optimization using KHA optimization algorithm.

***Table 4**. CTI value in the presence multi GCSC after optimization*

Primary relay	Backup relay	Without GCSC	With GCSC		
			$\beta = 5°$	$\beta = 45°$	$\beta = 90°$
5	6	0.3212	0.3171	0.3321	0.3324
11	12	0.3354	0.4211	0.3034	0.3097
15	16	0.3137	0.3156	0.3166	0.3135
33	34	0.3523	0.3044	0.4371	0.4278
35	36	0.3455	0.3577	0.3105	0.3044

Comparison with Published Results

For comparison purpose Table 5, presents a comparison of the best obtained value of the objective function (OF) for scenario without multi GCSC with other published results.

***Table 5:** Comparison of published results*

	MPSO [25]	LP [26]	NLP [26]	NM [26]	KHA
OF (sec)	61.7200	30.8451	18.0099	16.5948	**14.5384**

From the results of Table 3, it can be also seen that the proposed optimization algorithm KHA has given better performance and provides the best solution compared with other results.

CONCLUSIONS

In this paper we present an optimal relays coordination in the presence of multi GCSCs in the transmission power system for different conduction angle. We propose the formulation of the relays coordination problem as three scenarios. The obtained results show that the multi GCSC has a great impact on the setting and the coordination of the numerical directional overcurrent protections. Furthermore, the proposed optimization algorithm KHA show a high efficiency to solve such complex optimization problem, in such a way the coordination of the relays is guaranteed for all simulation scenarios.

The results showed that the proposed algorithms are able to find superior I_P and TDS and thus minimum operating time of the directional overcurrent relays and minimum CTI.The effectiveness of KHA can be observed from the results in terms of objective function values, which are better in comparison to other optimization algorithms used in the literature.

The continuity of this work will be the coordination of the overcurrent relays in the presence of FACTS devices and renewable energy considering several conflicting objective functions and various power system topologies (transmission and distribution) using new optimization algorithms, and hybrid optimization algorithms.

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