Optimal Over-current Relay Coordination Using Improved Harmony Search Method

Dusit Uthitsunthorn[1], Thanatchai Kulworawanichpong[2]

Abstract – *This paper presents optimal coordination of over-current relays by using improved harmony search method (IHS). The objective function of the relay coordination problem is to minimize the operation time of associated relays for given fault conditions in the protection system. The control variables used in this paper are the pickup current and the time dial setting of the relays. The proposed method was tested with 5-bus, WSCC 9-bus and standard IEEE 14-bus test systems. For benchmarking, sequential quadratic programming (SQP) and genetic algorithm (GA) were employed to solve this optimal relay coordination problem. The results showed that the IHS is capable to minimize the operation time of relays in the entire system. As a result, all search algorithms can solve optimal coordination relay which the improved harmony search method gives the best solutions for optimal coordination relay setting.*

Keywords*: Optimal Coordination, Time Dial Setting, Time Grand Margin*

NOMENCLATURE

α	Inverse tine coefficient constant
β	Inverse tine coefficient constant
I_p	Pickup current of the relay
I_{act}	Actual current seen by the relay
PSM	Plug setting multiplier
TGM	Time grading margin
Δt_{mb}	Operation time difference for each relays
t_m	Operating time of the main relay
t_b	Operating time of the backup relay
$t_{ij}^{\min}$	Lower limits of operating time of relay i
$t_{ij}^{\max}$	Upper limits of operating time of relay i
$TDS_{ij}^{\min}$	Lower limits of time dial setting of relay i
$TDS_{ij}^{\max}$	Upper limits of time dial setting of relay i
$Ip_{ijk}^{\min}$	Lower limits of pickup current of relay i
$Ip_{ijk}^{\max}$	Upper limits of pickup current of relay i
$rand(0,1)$	Random function in the range of [0,1]
x_i^L	Lower bound of the parameter i
x_i^U	Upper bound of the parameter i.
HMS	Harmony memory size
$HMCR$	Harmony memory consideration rate
$PAR^{\min}$	Lower limits of pitch adjustment rate
$PAR^{\max}$	Upper limits of pitch adjustment rate
M	Maximum iteration
k	Iteration index
$\overline{TDS}$	Time dial setting of inverse time relay
$\overline{Ip}$	Pickup current setting of inverse time relay
SQP	Sequential quadratic programming
GA	Genetic algorithms
IHS	Improved harmony search method

I. Introduction

Short-circuit events can occur unpredictably in any part of a power system at any time due to various physical problems. Such situations cause a large amount of fault current flowing through some power system apparatus. The occurrence of the fault is harmful and must be isolated promptly by a set of protective devices. Over several decades, protective relaying has become the brain of power system protection [1]. Its basic function is to monitor abnormal operations as a “fault sensor” and the relay will open a contractor to separate a faulty part from the other parts of the network if there exists a fault event [2],[3]. To date, power transmission and distribution systems are bulky and complicated. These lead to the need for a large number of protective relays cooperating with one another to assure the secure and reliable operation of a whole [4],[5]. Therefore, each protective device is designed to perform its action dependent upon a so-called “zone of protection” [6]. From this principle, no protective relay is operated by any fault outside the zone if the system is well designed. As widely known that old fashion analog relays are inaccurate and difficult to establish the coordination among protective relays, the relay setting is typically conducted based on the experience of an expert or only a simple heuristic algorithm. However, with the advancement of digital technologies, a modern digital protective relay is more efficient and flexible to enable the fine adjustment of the time-dial setting (*TDS*) different to that of the old fashion electromagnetic one.

This paper proposes an intelligent relay coordination method based on one of the most recently-used intelligent search algorithms, called the improved harmony search method (*IHS*) [7,8] for digital relaying, in which the time-dial setting is appropriately adjusted in order to minimize operating time while coordinated relays are also reliable. In this paper, the coordination of digital relaying systems is explained in Section II in such a way that the improved harmony search method in Section III is employed to achieve the system objective. Coordination case studies include the 5-bus, WSCC 9-bus and IEEE 14-bus test systems, where the setting of digital over-current relays was challenged and discussed in Section IV. The last section provides the conclusion.

II. Optimal Relay Coordination Problem

An optimal over-current relay coordination problem is a type of non-linear optimization problems in which all control variables are adjusted in such a way that the operation time of all associated relays to some specified faults of the entire protection system is optimized. This can be summarized as follows.

II.1. Non-linear Optimization Problem

The optimal over-current relay coordination problem is a non-linear optimization problem. It consists of a nonlinear objective function defined with non-linear constraints. Such a problem requires the solution of non-linear equations, describing optimal and/or secure operation of the protection systems. The general optimal over-current coordination problem can be expressed as a non-linearly constrained optimization problem as follows.

Minimize $f(x)$

Subject to $g(x) = 0$, equality constraints

$h(x) \leq 0$, inequality constraints

II.2. Characteristics of Over-current Relays

Over-current relays are devices which have ability to interrupt electricity supply service due to some excessive current of a severe fault. In a modern power system, network interconnection is very complicated. This affects the difficulty of key parameter setting of protective relaying devices [9],[10]. When a total number of over-current relays to be coordinated is increased or even feeding in closed-loop configuration is required according to a complex transmission network, over-current relay coordination setting is very difficult.

An over-current relay is a typical protective relay that allows a protected load operating within a preset value of the load current. The over-current relay is placed at the secondary side of the current transformer. The operating time of the over-current relay can vary due to relay type, time-dial setting and magnitude of fault currents. For the inverse time over-current relay, the operating time of the over-current relay can be expressed as shown in (1) and (2) according to the IEC standard 60255 [11].

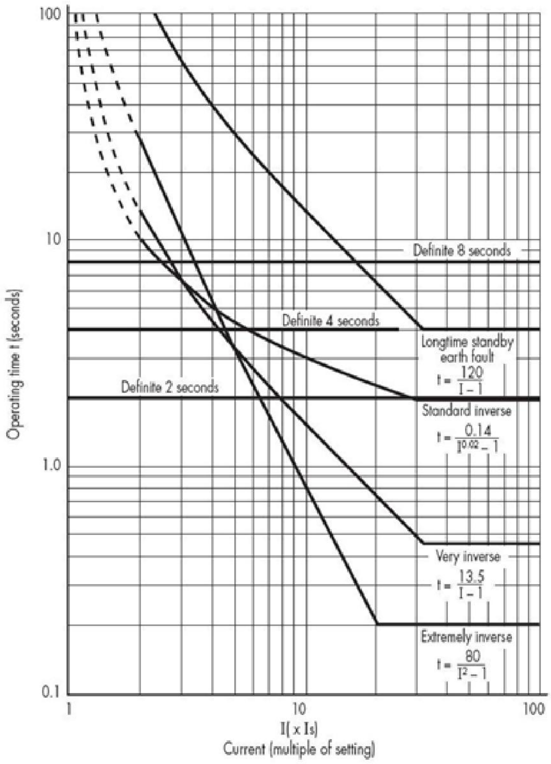

Fig. 1. IEC 60255 characteristic curves

$$t = \frac{\beta \times TDS}{PSM^{\alpha} - 1} \quad (1)$$

$$PSM = \frac{I_{act}}{I_P} \quad (2)$$

Where

α and β are arbitrary constant

PSM is the plug setting multiplier
I_{act} is the actual current seen by the relay
I_P is the pickup current of the relay

In this paper, a type of very inverse time over-current relay is used. Therefore, α is 1.0 and β is 13.5 can be specified according to the IEC standard 60255 as shown in Fig. 1.

II.3. Primary and Backup Relay Constraints

A primary or main protective device is a relay that is in the nearest position to the fault and must respond to the fault as fast as possible. To achieve a reliable protection system, backup relays are devices which will be initiated within a certain amount of time after the main relay fails to break the fault. An amount of delay time, called the time grading margin, must be added to the main relay operating time. This can be explained by Fig. 2 [12]. Relay *m* and *b* are the main and the backup relays, respectively. F_1 and F_2 are two fault cases seen by both relays. The operating time of the backup relay must be at least the operating time of the main relay plus the time grading margin for every fault case as shown in Fig. 3.

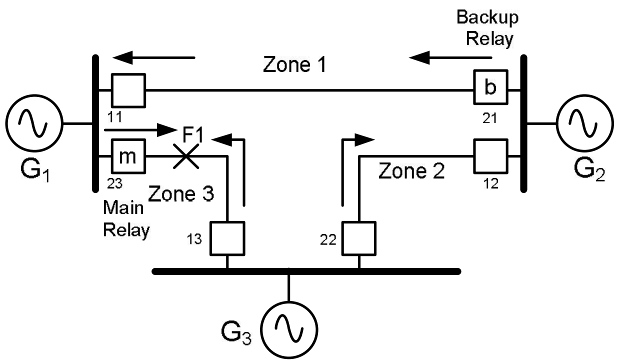

Fig. 2. Example network for over-current protection

To generalize the backup relaying constraint, (3) is defined as follows.

$$\Delta t_{mb} = t_b(F_i) - t_m(F_i) - TGM \geq 0,\ i \in FC \qquad (3)$$

Where
$t_b(F_i)$ is the operating time of the backup relay due to Fault F_i
$t_m(F_i)$ is the operating time of the main relay due to Fault F_i
TGM is the time grading margin, 0.3 – 0.5 s
FC denotes a set of fault cases

In practice, *TDS* and I_P of the over-current relay parameters can be adjusted in a certain interval. Their lower and upper limits are additional inequality constraints to this optimal over-current relay coordination problem as described follows.

$$TDS_{ij}\min \leq TDS_{ij} \leq TDS_{ij}\max \qquad (4)$$

$$Ip_{ij}\min \leq Ip_{ij} \leq Ip_{ij}\max \qquad (5)$$

$$t_{ijk}\min \leq t_{ijk} \leq t_{ijk}\max \qquad (6)$$

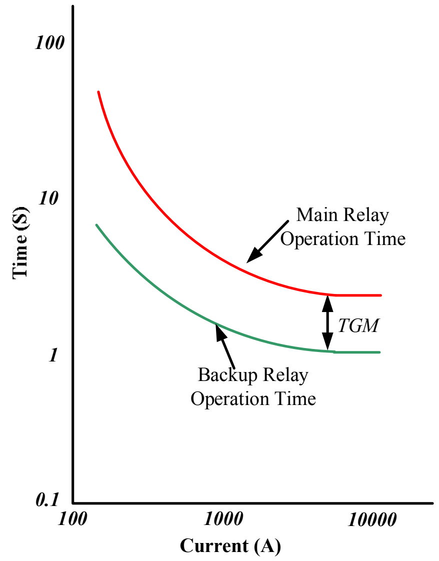

Fig. 3. Backup relaying constraint

II.4. Objective function

To coordinate the protective relays, the operating time of the main relay is minimized while satisfying the backup relaying constraint. As mentioned in the previous sub-section, the operating time of the backup relay is set as inequality constraints. The objective function used in this paper is given as follows.

$$f = w_1 \sum_{i=1}^{n} t_i^2 + w_2 \sum_{j \in FC} \left[\Delta t_{mb} - w_3(\Delta t_{mb} - |\Delta t_{mb}|) \right]^2 \qquad (7)$$

Where
w_1, w_2, w_3 is the weighting factors
n is a total number of relays

III. Optimization with Harmony Search

The optimization of physical systems is the process of adjusting control variables to find the values that achieve the best possible objective. To find optimal solutions for the optimal relay coordination problem, an appropriate optimization method has to be chosen to handle its non-linear and non-convex nature [13]. In fact, although there is no restriction for making selection, searching speed and accuracy are mainly the matter of concern. This paper attempts to demonstrate effectiveness of three different optimization techniques, namely *SQP, GA* and *IHS*. As widely known, *SQP* and *GA* have been commonly used across the globe in most applications including optimal relay coordination. There exist many optimization tools to implement *SQP* and *GA* for use e.g. MATLAB's Optimization TOOLBOX. In this paper, only the harmony search method is reviewed as described follows [14],[15].

The harmony search algorithm was conceptualized from the musical process of searching for a 'perfect state' of harmony, such as jazz improvisation. Jazz improvisation seeks a best state (fantastic harmony) determined by aesthetic estimation, just as the optimization algorithm seeks a best state (global optimum) [16],[17] determined by evaluating the objective function. Aesthetic estimation is performed by the set of pitches played by each instrument, just as the objective function evaluation is performed by the set of values assigned by each decision variable. The harmony quality is enhanced practice after practice, just as the solution quality is enhanced iteration by iteration. Consider a jazz trio composed of a saxophone, double bass, and guitar. Assume there exists a certain number of preferable pitches in each musician's memory: saxophonist {Do, Mi, Sol}, double bassist {Ti, Sol, Re}, and guitarist {La, Fa, Do}. If the saxophonist plays note Sol, the double bassist plays Ti, and the guitarist plays Do, together their notes make a new harmony (Sol, Ti, Do) which is musically the chord C7. If the new harmony is better than the existing worst harmony in their memories, the new harmony is included in their memories and the worst harmony is excluded from their memories. This procedure is repeated until a fantastic harmony is found. This can be described as shown in Fig. 4.

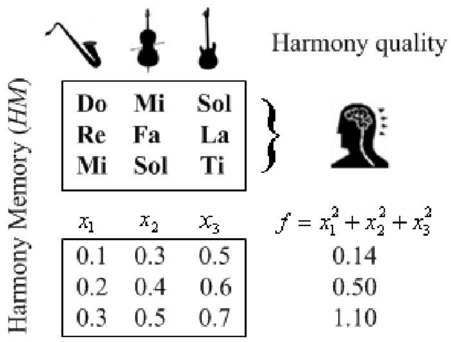

Fig. 4. Harmony search and real-valued optimization problem

However, its first version was invented as a combinatorial optimization where decision variables are discrete. To apply the harmony search method to the real world engineering in which many search spaces are continuous, some procedure of the harmony search method must be modified to be able to handle continuous search variables. Together, the parameter called bandwidth is used and adaptively changed by variance of population. Hence, it is an improved version of the harmony search method which is called as the improved harmony search method [18] - [21]. The steps in the procedure of the harmony search method can be described as follows. Further this can be summarized in Fig. 5.

Step 1: Assign setting parameters and control variables

1.1 Variable limits x_i^L and x_i^U

$$x_i^L \le x_i \le x_i^U \quad \text{where } i = 1, 2, 3\ldots, N$$

N is the total number of control variables

1.2 Assign the harmony memory size (*HMS*), where

$$10 \le HMS \le 100$$

1.3 Set *HMCR* (harmony memory consideration rate) as follows

$$0.0 \le HMCR \le 1.0$$

$$x_i' \leftarrow \begin{cases} x_i' \in \left\{x_i^1, x_i^2, \ldots, x_i^{HMS}\right\} \text{ with probability } HMCR \\ x_i' \in X_i \text{ with probability } (1 - HMCR) \end{cases}$$

1.4 Set *PAR* (pitch adjustment rate) as follows

$$0.0 \le PAR \le 1.0$$

$$x_i' \leftarrow \begin{cases} Yes \ \text{ with probability } PAR \\ No \ \text{ with probability } (1 - PAR) \end{cases}$$

1.5 Compute the step size (b) as described below

$$b(i) = \frac{x_i^U - x_i^L}{N} \tag{8}$$

1.6 Set the maximum number of iteration

Step 2: Initialize *HM* as expressed below

$$x_j^i = x_j^L + rand(0,1) \times \left(x_j^U - x_j^L\right) \quad (9)$$

The harmony memory is found as

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \quad (10)$$

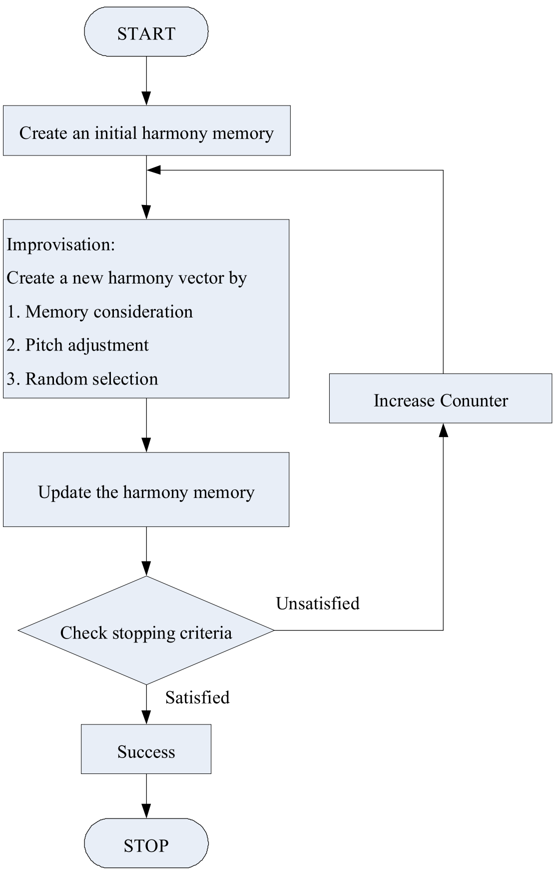

Fig. 5. Flowchart of the HS procedure

Step 3: Update each member for all solution vectors in *HM*

3.1 Generate a uniform random number, α ∈ [0,1]

If α ≤ *HMCR* Then

J = ceil(α× *HMS*)

$$x_j^i = x_J^i$$

END

3.2 Do the pitch adjustment by $b(i)$

If β ≤ *PAR* Then

$$x_j^i = x_j^i + (2\beta - 1) \times b(i) \quad (11)$$

END

Step 4: Keep the old solution or be replaced by a new one

Keep the old solution if the objective value of the updated one is not better than that of the old one. Otherwise, the old solution is replaced by the updated solution.

Step 5: After one of termination criteria is met

After one of termination criteria is met, the best solution in the recent harmony memory is the optimal solution found for this problem.

IV. Improved Harmony Search Method for Optimal Relay Coordination Problems

As described in the previous section, the *IHS* is inspired by the musical process of searching for a 'perfect state' of harmony. The most interesting feature of the *IHS* is that it does not require any prior knowledge or space limitations, such as smoothness or convexity of the function to be optimized. It exhibits a very good performance on the majority of the problems applied. To employ the *IHS* for solving optimal power flow problems, a brief description of the solution framework is given as follows.

IV.1. Modification of the pitch adjustment rate

In the *HS* algorithm, the pitch adjustment rate is arbitrarily fixed. Our *IHS* modifies this component. During any search iteration, *PAR* is varied and a simple linear relation is selected to define the modification as shown in (12) and also in Fig. 6.

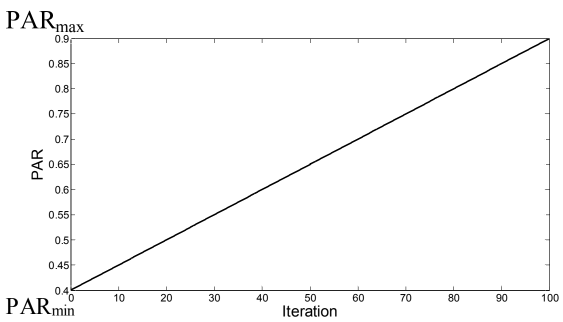

Fig. 6. Variation of pitch adjustment rate

$$PAR(k) = PAR_{\min} + \frac{k}{M}\left(PAR_{\max} - PAR_{\min}\right) \quad (12)$$

Where

PAR_{min} is the minimum value of PAR.
PAR_{max} is the maximum value of PAR.
M is the maximum iteration.
k is the iteration index.

IV.2. Control Parameters

Initially, the *IHS* was designed to work on a real-valued representation of the problem parameters. During the searching process, a musical notation as a collection of musical notes represents a solution vector. Let $\vec{x}_i$ be a created musical notation. The setting value of over-current relay in system ($\overrightarrow{TDS}, \overrightarrow{Ip}$) are typical members of the solution vector and it can be written as described in (13).

$$\vec{x}_i = \left[\overrightarrow{TDS} \quad \overrightarrow{Ip}\right]^T \tag{13}$$

IV.3. Objective Function and Its Fitness

The total operating time is computed as the sum of the individual of over-current relay in system and therefore used as the system objective function. To account for all the system constraints (4) – (6), the total operating times is augmented by non-negative penalty terms to penalize the constraint violations. Thus, the augmented cost function, called the penalty function [22], is formed as (14).

$$P(\vec{x}_i) = \sum_{i=1}^{N} f_i(t_i) + \Omega_E + \Omega_I \tag{14}$$

Where
Ω_E is the penalty terms to penalize equality constraints
Ω_I is the penalty terms to penalize inequality constraints

V. Simulation results and discussion

This section verifies the proposed algorithm for relay coordination. The objective is to minimize the different operating time between the primary and backup relays. The time grading margin is assigned as 0.3 s. *TDS* is in the range of 0.05-1.0 for all backup-primary relay pairs. The test systems used for this study are the 5-bus, WSCC 9-bus and IEEE 14-bus test systems. The weighting factors for optimal relay coordination to verify the effectiveness of the IHS are set as follows: w_1 = 1, w_2 = 100 and w_3 = 100. For comparison, sequential quadratic programming, and genetic algorithm were also employed. A total of 30 trials was conducted for each test case. Minimum, average, maximum and standard deviation (*SD*) of the obtained 30 trials were analyzed. All test cases were simulated by using the same computer of an Intel®, Core 2 Duo, 2.4 GHz, 3.0 GB RAM. The followings are summary of each test case.

Case I. The proposed method was tested with the 5-bus test system as shown in Fig. 7 [23]. Assume that loads were connected across bus 2, 3, 4 and 5 as 20+j10 MVA, 20+j15 MVA, 50+j30 MVA and 60+j40 MVA, respectively. The 14 over-current relays of the very inverse time type were used in this system. The zone protection and short circuit current of primary and back-up relay were shown in Table II.

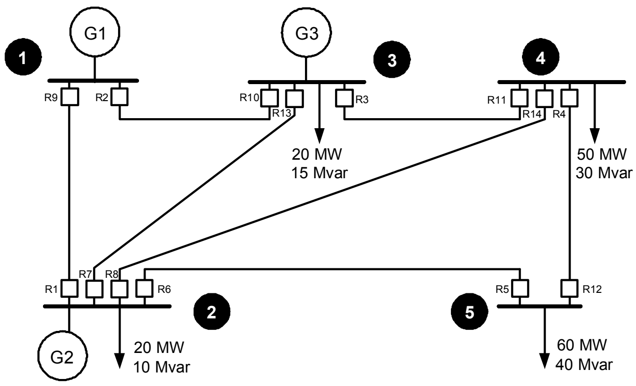

Fig. 7. The 5 bus test system

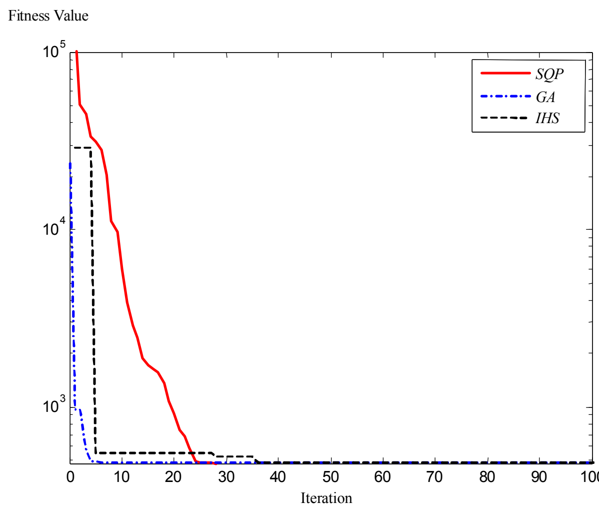

Fig. 8. Evolution of fitness value for 5 bus test system.

The results of time dial settings and pickup current setting of over-current relays for the system were shown in Table III. The results in Table I revealed the optimal value of objective function. It gave the best result when compared with those obtained from sequential quadratic programming and genetic algorithm. The minimum operation time acquired was 482.1135 s, 482.1135 s and 482.1135 s for sequential quadratic programming, genetic algorithm and the improved harmony search, respectively.

When considering the CPU time, the improved harmony search gave the time of 0.1173 s. The standard deviation of the *IHS* was as small as 0.1201 s.

TABLE I
COMPUTATIONAL RESULT FOR THE 5-BUS TEST SYSTEM.

Method	Objective function (sec)				CPU time(s)
	Min.	Average.	Max	*SD*	
SQP	482.1135	482.1160	482.1680	0.0101	0.0532
GA	482.1135	482.1135	482.1135	2.501e-6	14.913
IHS	482.1135	482.1505	482.7637	0.1201	0.1173

TABLE II
PRIMARY AND BACKUP INFORMATION FOR THE 5-BUS TEST SYSTEM.

Fault BUS	Main Relay	Backup Relay	Primary SC current	Secondary SC current	Line
1 Genl	9	10	7248.27	2576.53	1-3
	2	1	7773.89	7160.60	1-2
2 Gen 2	1	13	7248.27	1060.68	2-3
	1	14	7248.27	848.55	2-4
	1	5	7248.27	424.27	2-5
	7	14	8631.34	1415.92	2-4
	7	5	8631.34	707.96	2-5
	8	13	8993.04	1777.33	2-3
	8	5	8993.04	703.93	2-5
	6	13	9754.76	1797.38	2-3
	6	14	9754.76	1433.23	2-4
3 Gen 3	10	7	7773.89	1021.89	3-2
	10	11	7773.89	1226.26	3-4
	13	2	8631.34	942.46	3-1
	13	11	8631.34	2123.88	3-4
	3	2	8152.82	1273.79	3-1
	3	7	8152.82	1912.94	3-2
4	11	8	6962.53	6962.53	4-2
	4	3	1170.96	1170.96	4-3
	14	5	2341.92	2341.92	4-5
5	12	6	3540.91	3540.91	5-4
	5	4	6814.41	6814.41	5-2

Fig. 8 showed the convergence properties among the proposed method and the others. It illustrated the comparative convergence performance of the objective function. Remarkably, although the improved harmony search method convergences rapidly towards the solution, it also exhibits relatively smallest standard deviation.

<u>*Case II*</u>. This paper employed the WSCC 9-bus test system as shown in Fig. 9. It consisted of 3 generators, 6 lines, 3 transformers and 12 over-current relays. The load are connected across bus 5, 7 and 9 as 20+j15 MVA, 50+j30 MVA and 20+j10 MVA, respectively [24] - [26]. Information of the zone protection and short-circuit current of primary and back-up relays were shown in Table IV. The optimal solutions obtained for this test case were given in Table V.

TABLE III
OPTIMAL TIME DIAL SETTING AND PICK-UP CURRENT
FOR THE 5-BUS SYSTEM

Relay	Time Dial Setting (*TDS*)			Pick-up Current (*Ip*)		
	SQP	*GA*	*IHS*	*SQP*	*GA*	*IHS*
R1	0.5776	0.0500	0.8379	5.2713	12.000	5.1352
R2	0.7008	1.0000	0.3606	10.010	5.8333	9.1809
R3	0.8869	0.0500	0.9333	11.741	4.7430	10.226
R4	0.4964	1.0000	0.1984	4.2426	3.5800	6.2687
R5	0.1928	1.0000	0.5721	5.8561	4.5130	11.563
R6	0.4675	0.0500	0.4616	7.3171	9.3168	5.5740
R7	0.7555	0.0500	0.8038	7.0895	2.5910	2.8716
R8	0.3634	1.0000	0.8087	5.4397	3.6900	8.6721
R9	0.1554	0.0500	0.4544	10.710	8.1303	10.307
R10	0.0523	0.0500	0.8640	6.7021	4.0800	10.216
R11	0.1374	0.2777	0.1007	11.682	4.7430	6.4004
R12	0.5850	0.0500	0.4437	8.5793	12.000	4.1617
R13	0.7181	1.0000	0.5634	4.1765	2.5910	8.1426
R14	0.5791	0.0500	0.6069	4.6107	9.8520	4.1225

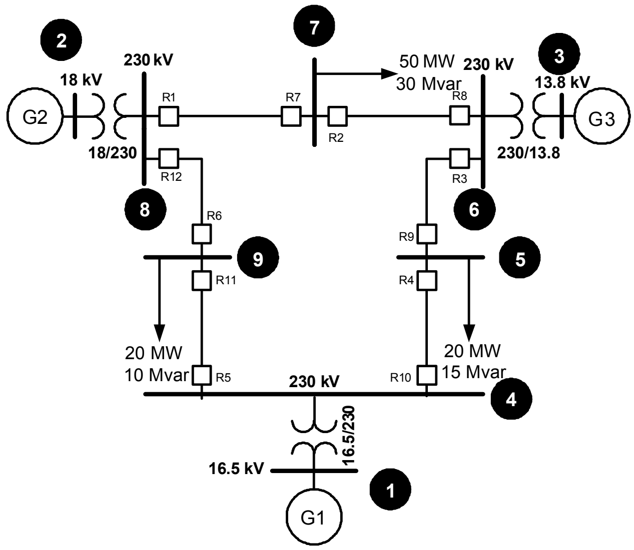

Fig. 9. WSCC 9 bus test system

TABLE IV
COMPUTATIONAL RESULTS FOR WSCC 9 BUS TEST SYSTEM.

Method	Objective function (sec)				CPU time(s)
	Min.	Average.	Max	*SD*	
SQP	3.5722	6.4226	86.7212	15.1721	0.0459
GA	3.5722	3.5722	3.5722	2.821e-7	9.3824
IHS	3.5722	3.5733	3.5908	0.0036	0.0972

TABLE V
PRIMARY AND BACKUP INFORMATION FOR
THE WSCC 9-BUS TEST SYSTEM

Fault BUS	Main Relay	Backup Relay	Primary SC current	Secondary SC current	Line
4 (Gen 1)	5	4	8204.39	3076.08	4-5
	10	11	8296.05	3182.82	4-9
5	4	3	7028.55	7028.55	5-6
	9	10	8274.09	8274.09	5-4
6 (Gen 3)	8	9	8075.53	2178.60	6-5
	3	2	8234.69	1978.90	6-7
7	7	12	8098.53	8098.53	7-8
	2	3	7296.58	7296.58	7-6
8 (Gen 2)	1	6	9749.44	4513.97	8-9
	12	7	10875.63	5633.89	8-7
9	11	12	7136.62	7136.62	9-8
	6	5	8183.53	8183.53	9-4

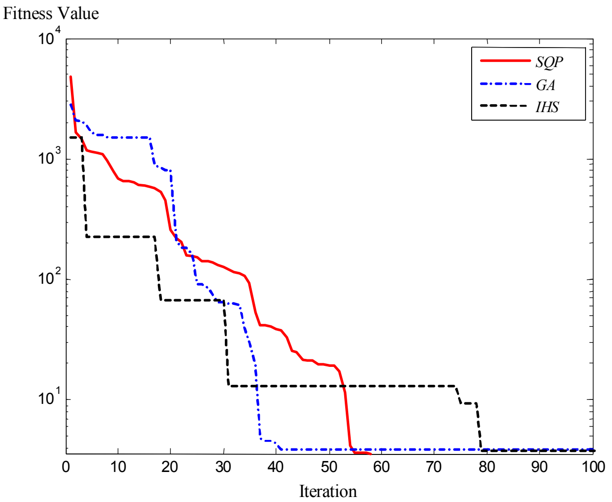

Fig. 10. Evolution of fitness value for WSCC 9 bus test system

The results showed the optimal setting value of the relay coordination time for the WSCC 9-bus test system. The *IHS* method gave the best results when compared with those obtained from sequential quadratic programming and genetic algorithm. The average operation times were 6.4226 s, 3.5722 s and 3.5733 s for sequential quadratic programming, genetic algorithm and improved harmony search, respectively. The improved harmony search gave the least CPU time consumed when compared with those of other methods.

TABLE VI
OPTIMAL TIME DIAL SETTING AND PICK-UP CURRENT
FOR THE WSCC 9-BUS TEST SYSTEM

Relay	Time Dial Setting (*TDS*)			Pick-up Current (*Ip*)		
	SQP	*GA*	*IHS*	*SQP*	*GA*	*IHS*
R1	0.0874	0.0500	0.2699	5.6756	4.0252	7.9117
R2	0.0507	1.0000	0.0616	3.7401	2.4960	2.5857
R3	0.1208	0.0500	0.0796	5.2423	11.736	9.3120
R4	0.0517	1.0000	0.1951	7.6956	2.1404	3.1467
R5	0.2820	1.0000	0.6067	8.2122	12.000	3.4021
R6	0.0501	1.0000	0.2524	7.1387	12.000	3.2866
R7	0.3693	0.0500	0.1943	4.1861	4.0252	7.0408
R8	0.2282	0.3472	0.5224	11.418	12.000	11.123
R9	0.0513	1.0000	0.1122	11.421	12.000	8.9069
R10	0.0505	0.0700	0.1048	9.7542	2.1404	2.4415
R11	0.0543	1.0000	0.3924	8.4945	12.000	3.4498
R12	0.0503	0.0500	0.1355	4.8806	12.000	3.6668

TABLE VII
PRIMARY AND BACKUP INFORMATION FOR THE IEEE 14-BUS TEST SYSTEM

Fault BUS	**Main Relay**	**Backup Relay**	**Primary SC current**	**Secondary SC current**	**Line**
1 (Gen1)	1	12	14,689.85	2,186.84	1-2
	2	3	19,415.45	7,376.35	1-5
2	3	7	14,689.85	1,162.20	2-1
	3	10	14,689.85	488.30	
	3	13	14,689.85	232.41	
	6	1	22,264.66	6,345.65	2-4
	6	10	22,264.66	1,990.35	
	6	13	22,264.66	1,935.10	
	5	1	23,003.82	6,362.65	2-4
	5	7	23,003.82	2,716.67	
	5	13	23,003.82	1,908.22	
	4	1	23,069.35	6,357.32	2-5
	4	7	23,069.35	2,722.79	
	4	10	23,069.35	1,969.74	
3	7	11	22,264.66	949.19	3-2
	8	6	11,325.47	580.43	3-4
4	9	5	3,192.71	3,192.71	4-2
	10	14	5,467.79	5,467.79	4-5
5	13	2	2,831.07	2,831.07	5-1
	14	4	3,293.31	3,293.31	5-2
	13	9	5,852.46	5,852.46	5-4
6 (Gen2)	17	24	77,524.56	564.51	6-12
	17	27	77,524.56	2,214.90	6-13
	15	22	80,132.39	4,429.87	6-11
	15	27	80,132.39	1,938.10	6-13
	16	22	80,494.12	4,536.14	6-11
	16	24	80,494.12	445.10	6-12
9	18	30	27,538.81	4,471.05	9-14
	19	21	29,663.69	6,961.43	9-10
10	20	18	17,348.97	17,348.97	10-9
	21	23	8,820.66	8,820.66	10-11
11	22	20	9,024.42	9,024.42	11-10
	23	17	16,068.79	16,068.79	11-6
12	25	15	12,437.68	12,437.68	12-6
	24	26	8,645.27	8,645.27	12-13
13	26	16	21,155.55	21,155.55	13-6
	27	25	5,438.20	5,438.20	13-12
	27	29	4,619.46	4,619.46	13-14
14	29	19	9,608.65	9,608.65	14-9
	30	28	7,742.59	7,742.59	14-13

TABLE VIII
OPTIMAL RESULTS FOR THE IEEE 14-BUS TEST SYSTEM

Method	Objective function (sec)				CPU time(s)
	Min.	Average.	Max	*SD*	
SQP	29.2163	29.2198	29.3176	0.0184	0.1345
GA	29.2163	29.2163	29.2164	1.7104e-6	32.0068
IHS	29.2163	29.2215	29.2642	0.0099	0.3365

For the average operation times of this test case were 29.2198 s, 29.2163 s and 29.2215 s for *SQP, GA* and *IHS*, respectively. However, when considering the average operation time, the IHS gave the least standard deviation at 0.0099 s with CPU time as 0.3365 s (see also Table VII).

Fig. 11 illustrated the convergence performance of objective function. Remarkably, although sequential quadratic programming convergences rapidly towards the solution, it exhibits relatively large standard deviation. In addition, the improved harmony search gave the most accurate and fastest convergence.

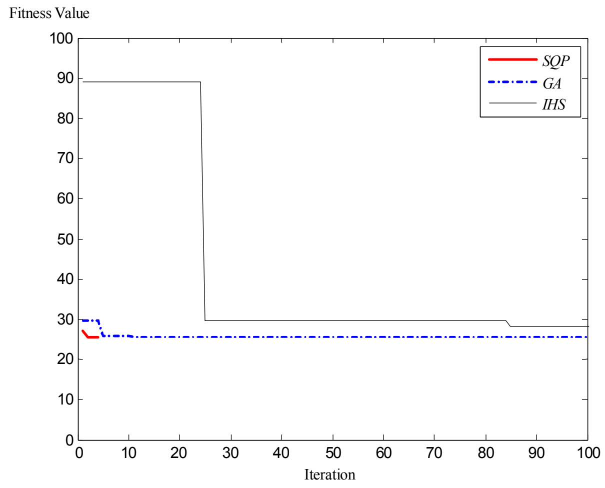

Fig. 11. Convergence for the IEEE 14-bus test system

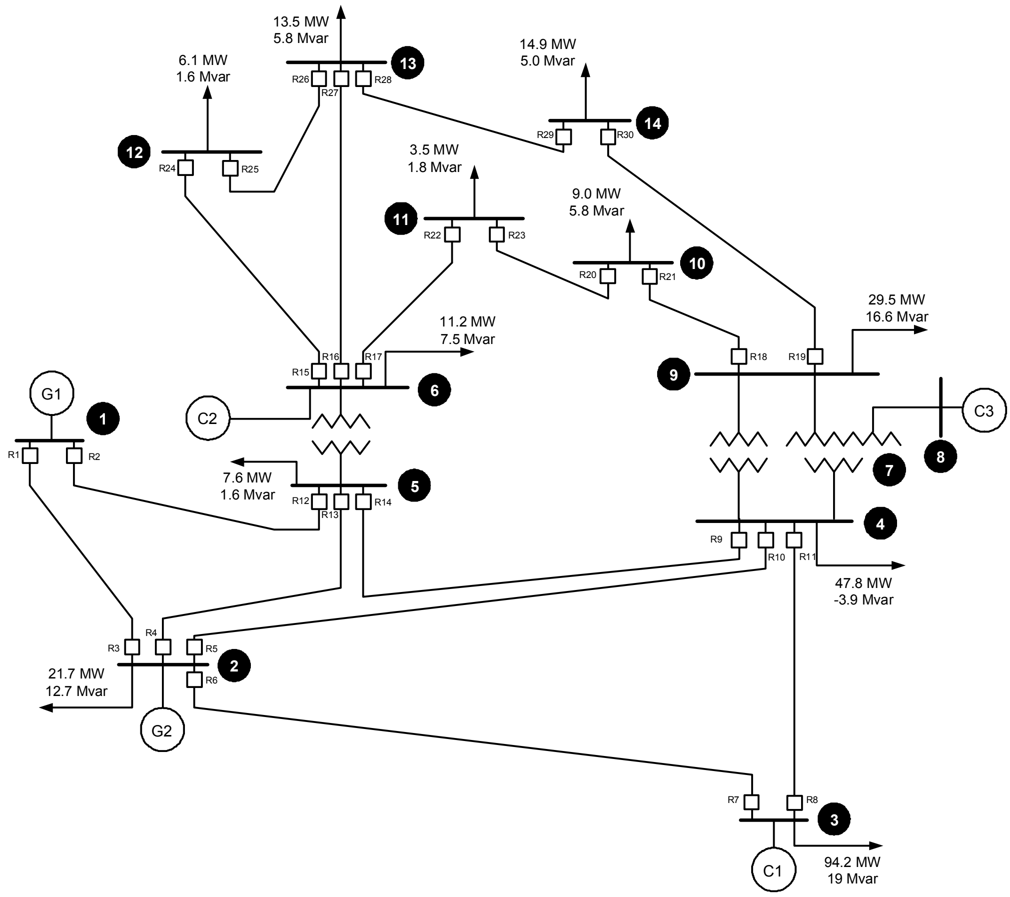

Fig. 12. IEEE 14-bus test system

TABLE IX
OPTIMAL RESULTS FOR THE IEEE 14-BUS TEST SYSTEM

Relay	Time Dial Setting (*TDS*)			Pick-up Current (*Ip*)			Relay	Time Dial Setting (*TDS*)			Pick-up Current (*Ip*)		
	SQP	*GA*	*IHS*	*SQP*	*GA*	*IHS*		*SQP*	*GA*	*IHS*	*SQP*	*GA*	*IHS*
R1	0.0576	1.000	0.4969	7.6931	12.000	5.5037	R16	0.4831	1.000	0.9142	11.696	9.8976	8.5981
R2	0.3514	1.000	0.7497	11.387	12.000	6.7494	R17	0.6903	1.000	0.2672	7.3757	12.000	11.487
R3	0.1128	1.000	0.2088	8.8128	12.000	9.9470	R18	0.2405	1.000	0.3857	4.7003	12.000	9.5177
R4	0.6746	1.000	0.3368	9.2120	12.000	5.5051	R19	0.2573	1.000	0.1207	11.113	4.8589	5.7136
R5	0.6482	1.000	0.9681	10.265	12.000	11.967	R20	0.5429	1.000	0.6812	9.5199	12.000	11.671
R6	0.1731	0.550	0.2592	11.623	12.000	10.863	R21	0.6236	1.000	0.1837	8.1904	12.000	10.376
R7	0.0518	1.000	0.5489	5.8764	12.000	11.627	R22	0.5497	1.000	0.6131	9.3355	12.000	9.8881
R8	0.2366	1.000	0.7141	10.306	11.566	5.6925	R23	0.0636	1.000	0.0689	6.4855	12.000	9.7267
R9	0.4156	1.000	0.6003	10.735	12.000	7.1704	R24	0.2625	1.000	0.7606	7.2896	12.000	10.888
R10	0.9188	1.000	0.6141	11.159	11.088	10.866	R25	0.6425	1.000	0.8155	8.5058	11.552	9.9164
R11	0.8356	1.000	0.0614	5.1813	12.000	4.5571	R26	0.9248	1.000	0.3561	10.752	12.000	11.532
R12	0.4822	0.956	0.4836	9.0327	12.000	7.3004	R27	0.6621	1.000	0.4975	11.764	12.000	4.9394
R13	0.4974	1.000	0.0651	10.794	12.000	11.407	R28	0.1407	1.000	0.5177	5.9192	12.000	10.537
R14	0.0536	1.000	0.2478	5.1104	11.996	7.4970	R29	0.5215	1.000	0.3903	6.7279	12.000	8.9934
R15	0.8636	1.000	0.9354	8.3197	11.608	7.2132	R30	0.1807	1.000	0.8069	5.2338	9.8116	5.4632

As a result, the *IHS* can find the same best solutions as *SQP* and *GA* do as shown in Table I, IV and VIII. However, the execution time of the *IHS* is just 0.1173 s, 0.0972 s and 0.3365 s for the 5-bus, WSCC 9-bus and IEEE 14-bus test systems, respectively, while *GA* is 14.913 s, 9.3825 s and 32.0068 s for the 5-bus, WSCC 9-bus and IEEE 14-bus test systems, respectively. These confirmed that the *IHS* can find the best solution of the optimal over-current relay coordination problems with the most accurate and fastest results.

V. Conclusion

In this paper, the implementation of the improved harmony search method (*IHS*) for solving the optimal over-current relay coordination problem was established. The effectiveness of the *IHS* method was verified by testing with the 5-bus, WSCC 9-bus and IEEE 14-bus test systems. The results of the proposed method were compared with those of the simulation results obtained by sequential quadratic programming (*SQP*) and genetic algorithms (*GA*). As a result, the *IHS* can find the same best solutions as *SQP* and *GA* do. Remarkably the execution time of the *IHS* is relatively shorter than that of GA. These confirmed that the *IHS* can find the best solution of the optimal over-current relay coordination problems with the most accurate and fastest results.

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