

Optimal Overcurrent Relay Coordination in Interconnected Networks by Using Fuzzy-Based GA Method

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Abstract--A new objective function (OF) has been proposed for mathematical formulation of directional overcurrent (OC) relay coordination in interconnected networks. The fuzzy based Genetic Algorithm (GA) is applied to optimize the proposed OF for optimal coordination of OC relays. The defined fuzzy rules update the weighting factors of OF during the simulation. The miscoordination problem of OC relays is solved while decreasing the operating time of the relays. The proposed method is implemented in three different networks and the simulation results have been compared with previous studies in order to illustrate the accuracy and efficiency of the proposed method to coordinate the directional OC relays with both discrete and continuous time setting multipliers (TSMs). The results have also been compared with the results of other optimization methods. Considering the coefficients of OC characteristic curves as the OF variables ensures that the proposed method has no limitation for the types of characteristic curves which will be utilized. Presenting the new term in OF, the performance of the proposed method has not been affected by the size of the networks.

Index Terms--Overcurrent relay, optimal coordination, interconnected network, time interval coordination, genetic algorithm, Fuzzy logic.

I. NOMENCLATURE

OC	Overcurrent relay
CTI	Coordination time interval between main and backup relays
PSM	Plug setting multiplier
TSM	Time setting multiplier
OT	Operation time
GA	Genetic algorithm
OF	Objective function
Δt_{mb}	Coordination time between the main and backup relays
$t_i(x_{close-in})$	Operation time of relay for the close-in fault
I_{Lmax}	Maximum load current passing through the relay
I_p	Minimum current detected as the fault current by the relay
I_{Fmin}	Minimum fault current in the protection zone of the relay

n	Number of relays
t_i	Operation time of relay for the close-in fault
t_m	Operation time of main relay for close-in fault of main relay
t_b	Operation time of backup relay for close-in fault of main relay
RCCC	Relay characteristic constant coefficients, RCCC: $\{A, B, C, D\}$
a_i	Parameters of objective function ($i = 1, 2, 3, 4$)
mb	Number of pair relays including main and backup relays
\bar{t}	Average of operation time of relays
$\Delta \bar{t}_-$	Average of negative coordination time between the main and backup relays
$\Delta \bar{t}_+$	Average of positive coordination time between the main and backup relays
\bar{n}_-	Average number of relays miscoordinations

II. INTRODUCTION

THE main duty of protective relays is to detect the faults and clear them in minimum time by sending the "open" signal to the circuit breakers. OC relay is one of the most common because of its simplicity and economic features. It has been used as the main relay to protect the subtransmission and distribution systems or as backup protection of the transmission system [1]. Both the main and backup relays detect and sense the fault as soon as it occurs. However, the primary relay is the first one which should clear the fault and the backup relay would take over tripping with a pre-determined time interval with the operation time (OT) of the main relay only if the primary relay does not eliminate the fault in its specific time [2]. The minimum OT of a backup relay should be more than the total of the related main relay OT, main circuit breaker OT, and overshoot time of the backup relay. Hence, the OC relays coordination can be considered a significant concern for power systems protection [3].

The settings of OC relays include plug setting multiplier (PSM) and time setting multiplier (TSM), which should be calculated such that the faulty part of the network is disconnected [4, 5]. Generally, in traditional OC relays, the rating of PSM is from 50 to 200% in steps of 25% and the

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rating of TSM is from 0.05 to 1 in steps of 0.05. However, these parameters can be set in a step of 0.01 in digital relays [6]. PSM is determined based on the minimum fault current and the maximum load current [7-9]. The coordination constraint between the main and backup relays can be

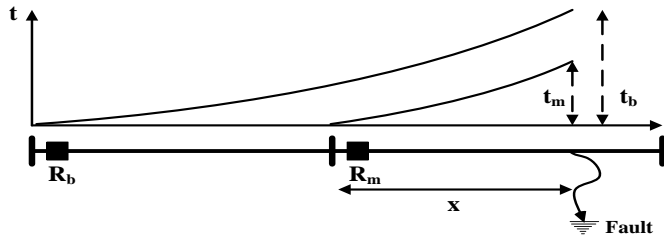


Fig. 1. Coordination constraint for a pair of main and backup relays

expressed as the following equation and is shown in Fig. 1 for a pair of main and backup relays:

$$\Delta t_{mb} = t_b - t_m - CTI \geq 0 \quad (1)$$

The coordination of OC relays in a radial network is really simple, since each relay is the backup for its downstream relays, while in interconnected networks each relay may be a backup for more than one relay and also several relays can be the backup for one relay. Although OC relays have a simple structure, their coordination can be an intricate problem in some interconnected networks. This problem would become more complex if the size and complexity of the system increases. It should be noted that in the interconnected system the directional OC relays should be used, which is simply addressed by the OC relay in this paper. The traditional methods for overcurrent relays coordination in interconnected networks are time consuming considering the large amount of calculation burden and the difficulty of determining the power system break point. Diverse ranges of optimization methods and approaches have been proposed to achieve not only the coordination between the relays but also the optimal operation time of the protection system. The objective functions used in these methods have some drawbacks related to operation time of relays and their coordination.

The Genetic algorithm (GA) has a wide range of uses in power systems, one of which is the OC relays coordination in an interconnected network. In [10], GA based methods for optimal coordination of OC relays have been proposed. This method suffers from miscoordination [6, 11], meaning that the operation time of backup relays are less than the main ones. In this condition, the coordination between the main and backup relays is not satisfied and the backup relay operates sooner than the main relay.

The continuous GA method has been used for optimal coordination in [12, 13]. However, this method has some drawbacks such as miscoordination. The other disadvantage related to this method is the way in which the value of TSM has been specified. Although the method claims that TSM is a continuous variable, it should be set in small steps even in modern and new digital relays. Therefore, by utilizing the continuous GA, the proposed methods in [12, 13] cannot find the optimum and best answer for discrete TSM without

approximation or rounding the continuous answer to the nearest discrete one.

The presented method in [6] has solved the problem of determining the continuous and discrete TSM but the OT of the main and backup relays is large which can be harmful for electrical equipment because they have to tolerate the fault current for a longer time. This has a strong negative effect on the efficiency of the equipment and the rate of their aging.

The new objective function (OF) has been proposed in [14] to overcome the negative aspects of [6]. However, this problem has not been solved appropriately due to the formulation and coefficients of OF. In other words, the weighting factors of different parts of OF have been determined through the trial and error approach in [6] and [14]. An advanced coordination method for an optimized protection time grading is proposed in [15]. The mentioned study is carried out based on new nonstandard tripping characteristics for OC protection relays to achieve the highest possible reduction of tripping times for a selective fault clearing in distribution networks protected by OC relays without communication links. In [15], the OC relay coordination is translated to a mathematical optimization task, which is solved by the method of Lagrange generalized with the Karush–Kuhn–Tucker conditions. However, as stated in the subsection IV.A in this paper, considering TSMs as continuous variables in the process of OC relays coordination with discrete TSM leads to a near optimal solution for the mathematically formulated OC relay coordination.

A comprehensive study of meta-heuristic methods which are applied to coordinate overcurrent relays is presented in [16]. It expresses the procedures of utilizing the meta-heuristic methods in OC relays coordination. These methods include GA, particle swarm optimization (PSO), differential evolution (DE), harmony search (HS), and seeker optimization algorithm (SOA). Moreover, some comparisons among these methods have been made by simulating different scenarios. The results in [16] indicate that the DE and HS obtain a better answer than the other mentioned optimization methods. In addition, the PSO and SOA reach their best answers faster than the other methods. Although the paper has compared the different optimization methods, there is no explicit expression about the method of determining the OF weighting factors. Apart from [16], diverse types of optimization methods which are applied to coordinate overcurrent relays have been studied in [17] and [18]. In addition, the interior point method (IPM) as a mathematical optimization method has been used in [19] and the results have been compared with other OFs. The results have been compared with two categories of optimization methods including metaheuristic ones (GA and DE) and hybrid ones (IPM-GA and IPM-DE). The proposed methods in [19] suffer from the similar drawback of [16]. In addition, the coefficients of characteristic curves have not been considered as the OF variables.

This paper presents a new accurate Fuzzy-GA based method for OC relays coordination in the interconnected network. The proposed method in this paper not only solves

the problems of miscoordination and high OT of relays by defining a new OF, but also uses new constraints for better coordination between the relays. The newly defined OF leads to finding the best answer for both the continuous and discrete variables.

The main contributions of the proposed methods are listed as follows:

- A new expression of OF is proposed in this paper in order to overcome the drawbacks existing in previous methods, i.e. high value for the relays OT and using approximation in determining the discrete variables from the achieved continuous answer.
- The weighting factors for different terms of OF are calculated based on a Fuzzy logic procedure instead of the trial and error approach to determine the most accurate values for OF parameters.
- The newly proposed algorithm is able to minimize the number of miscoordination in large networks in which all constraints cannot be satisfied by using previous methods.
- The characteristic curves coefficients of OC relays and PSMs are considered as the optimization problem variables to enhance the efficiency and flexibility of protection coordination in the proposed method. As a result, the best curve can be achieved for each main and backup relay. Therefore, there is no limitation for choosing or defining diverse kinds of characteristic curves in modern OC relays.
- The objective function presented in this paper uses the average operation time of the OC relays as well as average Δt between the main and backup relays. This noticeably decreases the dependency of the proposed method performance upon the size of the network utilized for simulation.

The rest of the paper is organized as follows: the problem formulation is described in Section III. Section IV explains the proposed method and its main concepts. Simulation results and their discussion are presented in section V. Finally, the conclusion is drawn in Section VI.

III. PROBLEM FORMULATION

The OC relays coordination in interconnected networks is complex due to the fact that there are a large number of constraints stated in the form of (1). Considering the fact that there is a low chance to coordinate the OC relays in an optimal way using the traditional methods, the coordination problem of OC relays in an interconnected network changes into an optimization problem with a large number of constraints.

There are three main points in the setting and coordination of OC relays, high speed operation of relay, selectivity which means that each relay should operate only for the faults occurring in the corresponding protection zone of the relay and reliability which means each relay must be appropriately backed up by some other relays. The mentioned concerns are considered in this paper to enhance the dependability of the protection system and consequently the security of the power system [20, 21].

In an interconnected network with a lot of OC relays, if the

OF is to optimize the operation speed of each relay separately, the problem will be very complex and practically insoluble. Hence, the overall speed operation of all relays should be considered. The following equation can be introduced to satisfy the OF for this consideration:

$$OF = \sum_{i=1}^n t_i(x_{close-in}) \quad (2)$$

The OC relays should be directional, i.e. each of them operates only for its protection zone. This means that they should detect faults only occurring in front of the relay. Moreover, the PSM of these relays should be properly set. This setting is defined as the minimum current which can be detected as the fault current by the relay. This current should be more than the maximum load current passing through the relay multiplied by a certainty factor (usually 1.3) and less than the minimum current for the fault occurring in the protection zone of the relay. This relation is expressed as follows:

$$1.3I_{Lmax} \leq I_p \leq I_{Fmin} \quad (3)$$

In addition, the minimum coordination time interval should be satisfied between the main and backup relays to ensure their selective operation. Considering all the above explanations, it can be concluded that for setting and coordination of OC relays in an interconnected network, the following optimization problem should be solved:

$$\begin{aligned} \text{Minimize } OF &= \sum_{i=1}^n t_i \\ \text{subject to: } \Delta t_j &= t_{b_j} - t_{m_j} - CTI > 0 \\ 1 &\leq j \leq mb \\ I_{pmin} &\leq I_p \leq I_{pmax} \\ TSM_{min} &\leq TSM \leq TSM_{max} \end{aligned} \quad (4)$$

The OT of a relay is related to its RCCC in terms of its setting parameters and the fault current flowing through the relay. Generally, the equation of the relay curve can be expressed as follows:

$$t = \left(\frac{A}{\left(\frac{I}{I_p} \right)^B - C} + D \right) TSM \quad (5)$$

In order to solve (4), both the mathematical methods and the intelligent searching algorithm methods can be used. Considering the large amount of inequality constraints in this optimization problem, the mathematical methods are not effective, while the intelligent searching methods can be a practical solution. In modern digital OC relays, PSM, TSM, and the relay characteristic curves coefficients can be set in very small steps. Consequently, the variables of the optimization problem can be discrete and continuous. The Genetic algorithm (GA) is one of the most robust tools for solving such a mixed integer optimization problem. Most intelligent searching algorithms solve the discrete problems in a continuous way and the answers are rounded to the nearest discrete variable at the end of each generation, while GA can

discretely solve the optimization problem with discrete variables during the solving process. This is the reason why the GA is used in this paper to solve the optimization problem. In order to use the GA, at first an OF should be defined appropriately including the related constraints. These constraints should be added as a penalty value to the OF in order to decrease the probability of selecting the chromosomes which do not satisfy the constraints by increasing the OF for them. Consequently, the final OF can be implemented as follows:

$$OF = \sum_{i=1}^n a_i f(t_i) + \sum_{j=1}^{mb} b_j g(\Delta t_j) \quad (6)$$

where, a_i and b_j are the constant coefficient as weighting factors.

Finally, GA chooses some chromosomes for crossover, mutation, and selection operators in proportion to their fitness. These operators generate a new population and it will be repeated until reaching the stop condition.

IV. PROPOSED METHOD

A. Continuity or Discreteness of TSM

In many studies, TSMs are considered as continuous variables in the process of the OC relays coordination with discrete TSM. Then, the feasible answers are achieved by rounding the continuous results to the nearest discrete TSM at the end of each generation or at the end of the program. This process has two main drawbacks:

- The number of possible states and the search space would be increased if the TSMs are considered as the continuous variables, while the answer can be found in a smaller discrete space. Therefore, the number of iterations for convergence is decreased. Moreover, in large networks, the search space may be so wide that it results in divergence of the optimization program.
- The relation between the fitness function and the problem variables is not clear or obvious in the scenario in which the optimization method works with continuous TSM and round it after optimization. Thus, it is a possible condition in which a global optimum is achieved by continuous TSMs but it would not be the global optimum among the discrete scenarios after rounding to a discrete TSM. As shown in Fig. 2, K_0 is a global minimum value considering continuous TSMs while K_1 , K_2 , and K_3 are the possible solution considering discrete TSMs. As shown in Fig. 2, it is obvious that if the continuous values of TSMs are considered, the optimization method is converged to the answer K_0 as the minimal value of the OF in continuous space. After rounding K_0 to a discrete variable, either K_1 or K_2 is obtained in the discrete space. However, scenario K_3 is the answer among the discrete scenarios and has a considerable difference with K_1 and K_2 .

According to the aforementioned issues, in this paper, a discrete gene is considered as a binary string in GA for the relay with the discrete TSM and a continuous gene as a real number for the continuous variables. Therefore, the searching

space becomes smaller and the chance for obtaining the correct answer is enhanced because the achieved optimal TSM is not rounded to the nearest discrete TSM.

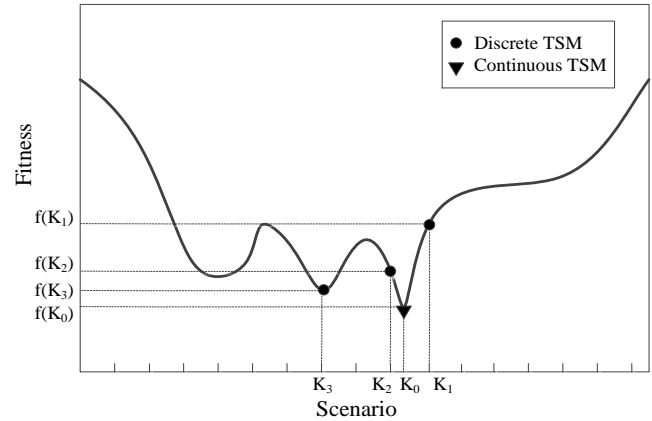


Fig. 2. An example of inappropriate use of continuous GA for discrete variables

B. Fitness Function

The following OF was proposed in [6] to coordinate the OC relays:

$$OF = \alpha_1 \sum_{i=1}^n (t_i)^2 + \alpha_2 \sum_{j=1}^{mb} (\Delta t_j - \beta(\Delta t_j - |\Delta t_j|))^2 \quad (7)$$

By comparing (7) and (6), it can be inferred that the main function in [6] has been defined as $f(t_i) = (t_i)^2$. In addition, the constraint has been added to the OF as $g(\Delta t_j) = (\Delta t_j - \beta(\Delta t_j - |\Delta t_j|))^2$. The presented OF in [6] has the following disadvantages:

- The main objective of the setting and coordination of OC relays in interconnected networks is to minimize the total OT of the relays. In this regard, using the square of OT in the OF leads to a distraction from the optimal answer. For more clarification, two scenarios are given as an example. It is assumed that the OT of the i -th and j -th relays are 0.1 and 0.9 for the first scenario and the similar variables for the second scenario are 0.4 and 0.813, respectively. The value of the main function is 0.82 for both scenarios (using $f(t_i) = \sum_{i=1}^n (t_i)^2$), while it is obvious that the first scenario presents the better answer because the average OT of the OC relay in the first scenario is less than the second one (0.5 and 0.6065, respectively). To correct the mentioned problem of the main function, this paper uses the $f(t_i) = t_i$ as the main OF.
- The penalty function presented in [6] is as $g(\Delta t_j) = \Delta t_j^2$, which has the same drawback above because of using the square of Δt_j , especially when this square value is applied in large networks which have more constraints. This problem usually creates the local optimums in the OF. In this condition, the probability of pining GA in these local optimums is enhanced. Thus, a linear penalty function as $g(\Delta t_j) = |\Delta t_j|$ is proposed in this paper. Furthermore, the penalty function for both positive and negative Δt are defined separately with

different coefficients as (8) since eliminating negative Δt s is more important than minimizing the positive ones.

$$\begin{aligned}
 g(\Delta t_j) &= b_1 g_1(\Delta t_j) + b_2 g_2(\Delta t_j) \\
 g_1(\Delta t_j) &= \left| \Delta t_j \right| - \Delta t_j \\
 g_2(\Delta t_j) &= \left| \Delta t_j \right| + \Delta t_j
 \end{aligned} \tag{8}$$

• In large networks with numerous OC relays, the number of constraints for the coordination problem is really high and in some conditions, there is no feasible answer in which all the main and backup relays are coordinated. In other words, it is possible that some constraints are not satisfied in the optimal solution. The number of constraints is important because additional costs should be paid for alternate backup protection for each of the relays related to the unsatisfied constraints. Thus, in order to reduce the number of unsatisfied constraints, the following function is proposed in this paper to add to the penalty function:

$$h(\Delta t_j) = \text{sgn}(\left| \Delta t_j \right| - \Delta t_j) = \begin{cases} 1 & \Delta t_j < 0 \\ 0 & \Delta t_j \geq 0 \end{cases} \tag{9}$$

where the $\text{sgn}(x)$ is the sign function which is equal to -1, 1 or 0 if x is negative, positive or zero, respectively.

As an example, suppose that there is a network with three OC relays which are coordinated by using two different scenarios. Table I shows the supposed value of Δt s obtained from these scenarios. As shown in Table I, there are 3 and 1 unsatisfied constraints by using the first and the second scenario, respectively.

Considering the penalty function as $g(\Delta t) = \Delta t^2$, the penalty values for these scenarios are 0.0075 and 0.6536, respectively. Based on the proposed method in [6], the results of the first scenario are considered as the answer, while it is obvious that the results of the second scenario are better because of its less unsatisfied constraints. However, considering the proposed penalty function in this paper, the penalty value for these two scenarios are 3.15 and 1.96, respectively. Thus, the proposed penalty function in this paper is more accurate than the previous methods such as [6].

Considering the above mentioned issues, the proposed OF is defined as follows in this paper to be minimized by GA:

$$\begin{aligned}
 OF &= a_1 \frac{\sum_{i=1}^n t_i}{n} + a_2 \frac{\sum_{j=1}^{mb} \left(\left| \Delta t_j \right| - \Delta t_j \right)}{\max(1, \sum_{j=1}^{mb} \text{sgn}(\left| \Delta t_j \right| - \Delta t_j))} + \\
 & a_3 \frac{\sum_{j=1}^{mb} \left(\left| \Delta t_j \right| + \Delta t_j \right)}{mb - \sum_{j=1}^{mb} \text{sgn}(\left| \Delta t_j \right| - \Delta t_j)} + a_4 \frac{\sum_{j=1}^{mb} \text{sgn}(\left| \Delta t_j \right| - \Delta t_j)}{mb}
 \end{aligned} \tag{10}$$

Each term in the proposed OF is normalized with respect to the number of non-zero terms in each summation to decrease the dependency of coefficients on the number of relays and

coordination constraints as well as to determine the thresholds of coefficients in the Fuzzy process.

TABLE I
 Δt FOR TWO SUPPOSED SCENARIOS

Δt	Results of the First Assumed Method	Results of the Second Assumed Method
1	-0.05	0.06
2	-0.05	0.10
3	-0.05	-0.80

C. Determination of Fitness Function Coefficients

The OF stated in (7) has three coefficients, a_1 , a_2 and β which are constant and defined based on the trial and error approach in [6]. However, they are highly related to the nature of the problem and under-studied network. Therefore, they should be determined separately in each network. Moreover, since these coefficients are constant during the optimization procedure, GA may converge to a local optimal point and the global optimum is missed.

The qualifiers such as very small, small, average, large, and very large (i.e., SS, S, N, L, and LL, respectively) are used to describe the Fuzzy rules which are the relationships between the inputs and outputs of a Fuzzy function. In this regard, this paper proposes a Fuzzy logic with the rules listed in Table II. Some of these rules are derived based on the mathematical expression of (10).

The proposed OF in (10) has four parameters, a_1 influences the value of relays OT which is shown as \bar{t} in Table II, a_2 has an effect on negative Δt s which is shown as $\Delta \bar{t}_-$ in Table II, a_3 has an impact on large value of Δt s which is shown as $\Delta \bar{t}_+$ in Table II, and a_4 decreases the number of unsatisfied constraints which is shown as \bar{n}_- in Table II. However, the other Fuzzy rules have been derived based on observation of input-output behaviors. As an example and further clarification about the interpretation of Fuzzy functioning in this paper, the first row of this table expresses that if \bar{t} (the average of relays operation time) is a large value and \bar{n}_- (the number of constraints which are not satisfied) is a very small value, the following measures should be taken without considering the values of $\Delta \bar{t}_-$ and $\Delta \bar{t}_+$:

- The value of a_1 should be very large
- The value of a_3 should be very small
- The value of a_2 and a_4 should remain without any change.

As a cycle, the proposed Fuzzy logic determines the parameters a_1 , a_2 , a_3 , and a_4 considering the outputs of GA after a preset number of GA iterations which is called maximum Fuzzy generation (e.g., 50 iterations). In other words, for example, GA is run for 50 iterations. Then, Fuzzy logic uses the outputs of GA after these iterations to reproduce the OF parameters through the Fuzzy rules. This procedure will be repeated after each of the 50-iterations to reach the maximum number of generations.

TABLE II
THE RULES OF FUZZY LOGIC

\bar{t}	$\Delta\bar{t}_-$	$\Delta\bar{t}_+$	\bar{n}_-	a_1	a_2	a_3	a_4
L	**	**	SS	LL	**	SS	**
L	**	**	S	L	**	SS	**
L	**	**	L	S	**	SS	**
N	**	**	SS	L	**	S	**
N	**	**	S	N	**	S	**
N	**	**	L	SS	**	S	**
S	**	**	**	N	**	**	**
SS	**	**	**	S	**	**	**
SS	**	L	**	**	**	LL	**
S	**	L	**	**	**	L	**
N	**	L	**	**	**	N	**
L	**	L	**	**	**	SS	**
SS	**	N	**	**	**	LL	**
S	**	N	**	**	**	N	**
N	**	N	**	**	**	N	**
L	**	N	**	**	**	SS	**
**	**	S	**	**	**	S	**
**	**	SS	**	**	**	S	**
**	L	**	**	**	LL	**	**
**	N	**	**	**	N	**	**
**	S	**	**	**	S	**	**
**	SS	**	**	**	S	**	**
**	**	**	SS	**	**	**	SS
**	**	**	S	**	**	**	L
**	**	**	L	**	**	**	LL

D. Coefficients of Characteristic Curves

Most papers presented in the field of OC relays coordination have considered only the TSM of relays as the optimization variable [6, 11]. However, some papers have considered the types of standard characteristic curves as the variables of their OFs [22]. In modern digital relays, some variables can be set almost as continuous ones in a defined range. In this regard, [22] has not taken benefits of this important feature of the modern digital relays because it has considered all of their variables as discrete ones. The equation of the characteristic curves can be expressed as (5). Therefore, the types of curves are predetermined based on their specific coefficients, while these coefficients can be set in modern digital relays [23]. These coefficients are considered as variables in the proposed OF. This point ensures that the proposed method does not have any limitation for using the different kinds of characteristic curves in its algorithm.

The objective function presented in this paper uses the average operation time of the OC relays as well as average Δt between the main and backup relays. However, the objective functions in the other articles use the sum of operation time of OC relays and sum of Δts . This is the reason why the coefficients of the objective functions in those methods are strongly dependent upon the number of the relays utilized in a network. Moreover, these methods use the trial and error approach for determining the coefficients of their objective functions. Therefore, when they are applied to a larger network, the chance of finding the optimum answer decreases; hence the calculation time increases. On the other hand, the

coefficients of the objective function proposed in this paper are modified during the simulation process.

The following procedure explains the steps of the proposed method when it is applied to a network regardless of its size.

Step 1: Data acquisition of the network such as transmission lines, generators, and transformers.

Step 2: Load flow study for determining the maximum load currents for each relay.

Step 3: Determining the pairs of primary and backup relays.

Step 4: Calculation of the minimum fault current (I_{Fmin}) and maximum fault current (I_{Fmax}) flowing through each relay based on the proposed method in [24] using impedance matrix Z_{bus} of the network.

Step 5: Determining the allowable range for the PSM and TSM of each OC relay based on the catalog instruction and according to (4).

Step 6: Determining the characteristic curves of each OC relay. Then, each type of these curves is numbered and the function and the operation time will be defined. For example, assume that there are four types of characteristic curves. Table III indicates the tag of each curve for this example.

TABLE III
EXAMPLE OF NUMBERING THE CHARACTERISTIC CURVES

Type of Curve	Tag Number
IEC Normally Inverse	1
IEC Very Inverse	2
IEEE Extremely Inverse	3
Inverse User-Defined	4

Then, the function of operation time for each OC relay will be defined. With respect to Table III, the operation time of OC relay in IEC Normally Inverse curve, which is called f_1 , can be written as follows:

$$t = \frac{0.14 \times TSM}{(PSM)^{0.02} - 1} \quad (11)$$

Step 7: Calculation of the maximum faults currents flowing through each pair of primary and backup relays as a close-in fault of the primary relay.

Step 8: Determining the problem variables for creating the chromosomes in GA as shown in Fig. 3.

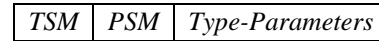


Fig. 3. The defined chromosome in the proposed method

where, $TSM = [TSM_1, TSM_2, \dots, TSM_n]$ and $PSM = [PSM_1, PSM_2, \dots, PSM_n]$ and $Type\text{-}Parameters = [Type\text{-}Parameters_1, Type\text{-}Parameters_2, \dots, Type\text{-}Parameters_n]$. $Type\text{-}Parameters_n$ includes the defined number of each characteristic curve based on step 6 and its coefficients. For instance, assume an inverse user-defined characteristic curve, which has been numbered 4 in step 6. This curve has an equation similar to (5). Then, the variable $Type\text{-}Parameters$ for the assumed curve is given below:

$$Type\text{-}Parameters = [4, A, B, C, D] \quad (12)$$

Step 9: This is the final step. In this step, the GA starts to work with the defined chromosomes in step 8. After a predefined number of iterations, the weighting factors will be updated through the defined fuzzy rules and the GA starts to work with the new weighting factors. It will be repeated until reaching the best answer.

It is obvious that steps 1-8 are not affected by the size of the network. Sometimes, these data could be prepared before starting the main algorithm.

The final step (i.e., step 9) uses fuzzy rules and GA both of which are general tools for applying to different kinds of problems. However, applying GA to a larger network with more variables will increase the simulation time but the accuracy of the proposed method will not decrease.

The proposed method procedure is shown in the flowchart of Fig. 4. In this figure, G is the number of iterations and F is the preset number of GA iterations before each usage of Fuzzy logic.

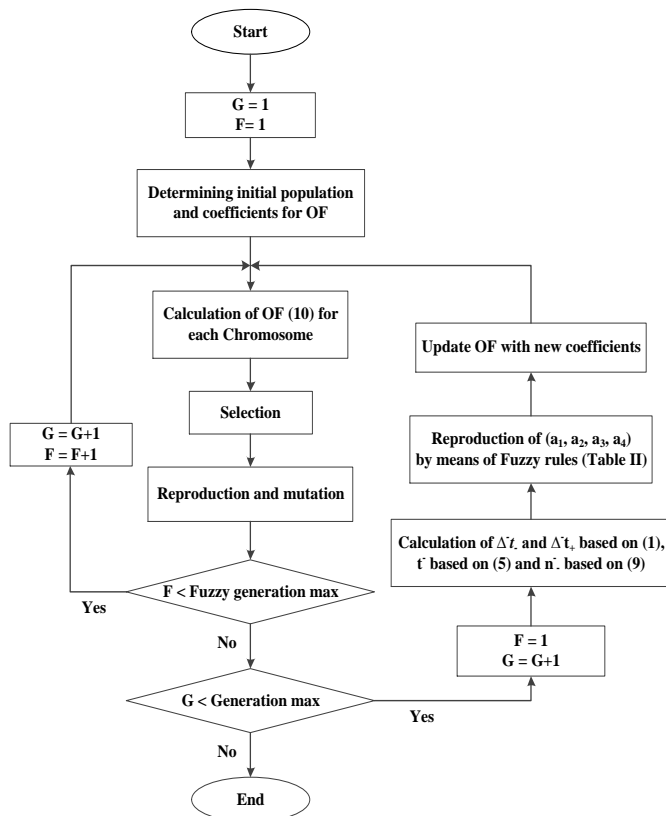


Fig. 4. Flowchart of the proposed method

V. SIMULATION RESULTS AND DISCUSSION

In order to investigate the accuracy and efficiency of the proposed method, it is applied to three different networks including 6-bus, 8-bus and IEEE 30-bus test systems. In addition, three scenarios are defined. The results of the proposed method are compared with [6] in the first and second scenarios and with [19] in the third scenario. In the first scenario, PSMs and relays operation characteristics are defined similar to [6] because the best comparison can be

achieved when the parameters are the same for both methods. Moreover, by considering the similar parameters with [6], the efficiency of the proposed OF in [6] and this paper can be compared precisely. The additional optimization variables such as PSM and the coefficients of characteristic curves are considered in the second scenario to show the best operation of the proposed method. In the third scenario, the proposed method in this paper is compared with the presented methods in [19]. These methods include different types of optimization methods which have been applied to the problem of coordination of OC relays in interconnected networks.

The values of maximum load current have been obtained through MATLAB software. The test systems have been simulated in the mentioned software based on the given data in [24] and [25] for the first and second test systems, respectively. Then, the load flow program is run and the values of maximum load current are achieved.

The values of minimum and maximum fault currents have been determined by the proposed method in [24]. The paper presents a new accurate method for determining the critical fault point based on which the maximum and minimum values of fault current can be obtained. This method analytically calculates the impedance matrix Z_{bus} of the network. The critical fault point is determined through the calculated impedance matrix. In the proposed method, a hypothetical bus X is considered as the fault location in each line of an interconnected network. Then, it is moved from the beginning to the end of each line and impedance matrix Z_{bus} will be calculated for each of these movements. In order to update the Z_{bus} for each step, the admittance matrix Y_{bus} of the network is applied. The Y_{bus} is used because of its simple rules for construction. Finally, the critical fault point is determined for each line and the values of maximum and minimum fault currents will be obtained.

A. Scenario 1

In this scenario, the proposed method is applied on an 8-bus network. In this scenario, the optimization variable is just TSM to show the efficiency of the proposed expression of OF and its weighting factors in comparison with the presented methods in [6]. The network and its data can be found in [24]. The weighting factors of OF obtained by Fuzzy rules are listed in Table IV. TSM, PSM, and OT of the relays in this network are listed in Table V for both proposed methods in this paper and [6]. As shown in Table V, the proposed method in this paper results in decreasing the TSM and the OT of the relays compared to [6].

The current of close-in fault for each pair of relays are listed in Table VI by using the proposed method in this paper. Also, the value of Δt achieved by the proposed method in this paper and [6] is shown in this table. These results illustrate that the proposed method in this paper not only decreases the OT of the relays but also keeps the coordination of all their pairs. Better results are achieved since the coefficients are determined through Fuzzy logic. Fig. 5 shows these coefficients variations during the Fuzzy process. It is obvious

that the mentioned coefficients are converged to their optimum value considering the defined rules.

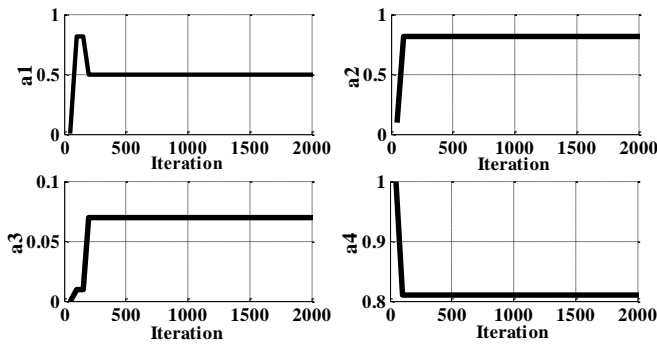


Fig. 5. Convergence of OF's coefficients in the first scenario

TABLE IV
THE PROPOSED OF'S COEFFICIENTS IN THE FIRST SCENARIO

Weighting Factor	Value
a_1	0.50
a_2	0.81
a_3	0.70
a_4	0.81

TABLE V
PSM, TSM, AND OT OF THE RELAYS IN THE FIRST SCENARIO

Relay No.	Proposed method in [6]			Proposed Method		
	PSM (A)	TSM (s)	OT (s)	PSM (A)	TSM (s)	OT (s)
1	500	0.15	0.5894	500	0.1	0.3929
2	800	0.35	1.2173	800	0.3	1.0434
3	600	0.25	0.9621	600	0.25	0.9621
4	800	0.1	0.6636	800	0.1	0.6636
5	550	0.1	0.766	550	0.05	0.383
6	550	0.25	0.7623	550	0.2	0.6099
7	650	0.2	0.7059	650	0.2	0.7059
8	550	0.25	0.7625	550	0.2	0.61
9	540	0.05	0.3479	540	0.05	0.3479
10	550	0.15	0.6883	550	0.15	0.6883
11	650	0.25	0.9834	650	0.25	0.9834
12	550	0.4	1.1847	550	0.4	1.1847
13	600	0.1	0.4665	600	0.1	0.4665
14	800	0.15	0.5944	800	0.15	0.5944
Sum		2.75	10.694		2.5	9.636

B. Scenario 2

In this scenario, the IEEE 30-bus test system is simulated to show the proposed method effectiveness in optimal relay coordination. The network and its data can be found in [25]. In this scenario, TSM, PSM, and the coefficients of characteristic curves are considered as the optimization variables. The proposed OFs stated in this paper and [6] are simulated in this scenario. The weighting factors of OF obtained from the fuzzy controller are listed in Table VII. TSM, PSM, and OT of the relays in this network are listed in Table VIII for both OFs proposed in this paper and [6]. Moreover, the coefficients of characteristic curves obtained from both OFs are listed in this table. However, the value of D is considered to be equal to zero similar to IEC standards [26]. The value of Δt for the

proposed methods in this paper and [6] is shown in Table IX. This table indicates that there are 17 miscoordinations in the results obtained from [6], while the number of miscoordinations is only two by using the proposed OF in this paper because of adding a new term to the OF as explained in section IV.B which diminishes the number of miscoordinations.

TABLE VI
CLOSE-IN FAULT CURRENT VALUE FOR EACH PAIR OF RELAYS AND Δt FOR EACH PAIR OF RELAYS IN THE FIRST SCENARIO

Main relay	Backup relay	Main relay close-in fault current (kA)	Backup relay close-in fault current (kA)	Δt Proposed in [6] (s)	Δt Proposed method (s)
8	7	4.9618	1.5209	0.4673	0.6198
2	7	5.3623	1.5281	0.0028	0.1767
2	1	5.3623	0.8049	0.6290	0.0541
3	2	3.3345	3.3345	0.2675	0.0332
4	3	2.2343	2.2343	0.2057	0.2057
5	4	1.3529	1.3529	0.1885	0.5715
6	14	4.965	1.5229	0.4825	0.635
14	1	4.2327	0.7941	1.3181	0.5473
1	6	2.6825	2.6825	0.0532	0.0411
9	10	1.4437	1.4437	0.3173	0.3173
10	11	2.3347	2.3347	0.2195	0.2195
11	12	3.4808	3.4808	0.0492	0.0492
12	14	5.3651	1.5294	0.0489	0.0489
12	13	5.3651	0.8056	0.8135	0.8135
13	8	2.4907	2.4907	0.2292	0.0101
7	13	4.2326	0.8098	1.4085	1.2523

In comparison with [6], the OT of relays is decreased by using the proposed Fuzzy logic in this paper. The convergence diagrams of the coefficients of the proposed OF are shown in Fig. 6. Using the Fuzzy logic and defining the appropriate rules play an important role in proper determination of OF parameters instead of the trial and error approach. This leads to better performance and more acceptable answers of OF. Defining the appropriate rules for the coefficients fuzzification leads to proper convergence and acceptable answers for the coefficients by which the OT of the relays and the number of miscoordination have been minimized. The results confirm that the proposed method has no limitation for using the diverse characteristic curves and determines their coefficients such that the best answer is achieved.

C. Scenario 3

In order to validate the better performance of the proposed method, it is compared with diverse optimization methods including DE, IPM-GA, IPM-DE, IPM-branch and bound method (IPM-BBM), and IPM-IPM [19]. In this regard, the 6-bus test system is used, the data of which can be found in [19]. There are 22 OC relays with the characteristic curves of IEC normally inverse. 52 pairs of primary and backup relays are identified in this network. The values of maximum load current, minimum fault current, and maximum fault current

flowing through each relay can be found in [19]. The current transformers ratios for each relay and the close-in fault current value for each pair of relays have been presented in [19]. The TSM values of the relays are considered as continuous variables changing from 0.1 to 1.1. In addition, it is assumed that the PSM values of the relays are discrete variables varying from 0.5 to 2 in the step of 0.25.

TABLE VII
THE PROPOSED OF COEFFICIENTS IN THE SECOND SCENARIO

Weighting Factor	Value
a_1	0.2204
a_2	0.1573
a_3	0.0709
a_4	0.5015

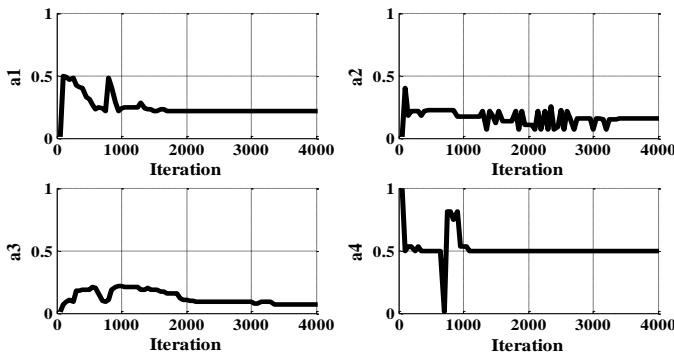


Fig. 6. Convergence of OF's coefficients in the second scenario

The results of comparison of the proposed method with other ones in [19] are listed in Table XI. These results include the optimal TSM and PSM values as well as the total operation time of the relays. The method in [19] chooses the best answer among the ones resulted from 100 simulations. Furthermore, the weighting factors of objective function are determined by a trial and error approach. On the other hand, the simulation results of the proposed algorithm in this paper are obtained just by one simulation and the algorithm by itself calculates the weighting factors of the objective function effectively. The values of these coefficients are listed in Table X. These values are calculated based on the defined fuzzy rules in this paper. Based on the presented results in the last row of Table XI, the operation time of OC relays (i.e., $\sum_{i=1}^{22} t_{op,i}$) for the proposed method is less than the other ones while there is no miscoordination among the pairs of primary and backup relays.

VI. CONCLUSION

In this paper, a Fuzzy-GA based method with a new OF has been proposed for optimal coordination of OC relays in interconnected networks. This method solves both miscoordination problems as well as the large OT of relays. Moreover, both discrete and continuous TSMs can be directly obtained through the proposed OF. PSM and the coefficients of characteristic curves of OC relays are other variables of the presented OF. These coefficients can be set in modern digital relays and this fact can result in better coordination and less OT. It confirms that the proposed method is capable to use any

kind of characteristic curves. In addition, the weighting factors of OF are determined by the Fuzzy logic process in order to overcome the drawbacks existing in previous works for finding these factors. The proposed method is tested on three different networks including the 6-bus, 8-bus, and IEEE 30-bus test systems. The results of the proposed method have been compared with the different previous ones. The simulation results approve the effectiveness and accuracy of the proposed method because of its new expression for OF and its comprehensive variables.

TABLE IX
 Δt FOR EACH PAIR OF RELAYS IN THE SECOND SCENARIO

Main Relay	Backup Relay	Δt Proposed in [6] (s)	Δt Proposed method (s)	Main Relay	Backup Relay	Δt Proposed in [6] (s)	Δt Proposed method (s)
1	21	0.2829	0.1161	10	29	0.4748	0.0121
1	22	-0.0223	0.0281	9	31	3.2547	0.0017
2	22	-0.0775	0.0395	11	29	0.548	0.1034
3	21	0.0573	0.0029	10	31	3.2886	0.0404
23	2	0.3652	0.1876	11	30	0.2082	0.2208
5	2	0.2524	0.0854	12	10	0.1018	0.1073
21	25	0.2	0.0507	30	32	-0.0997	0.0126
13	2	0.1378	0.1113	32	11	0.0188	0.3939
21	33	0.0165	0.0819	31	12	0.0251	0.1386
4	3	-0.0145	0.3203	14	11	0.059	0.4679
22	24	-0.1701	0.0117	31	34	-0.0144	0.2493
23	25	0.2587	0.0872	14	12	0.000	0.0231
23	33	0.0752	0.1186	32	34	-0.0848	0.0606
29	4	0.8823	0.0301	15	13	0.4422	0.0033
24	9	-0.039	0.099	33	35	-0.085	0.001
6	5	0.0015	0.0089	35	14	-0.0224	0.0885
25	26	0.016	-0.0113	34	15	0.2844	0.0052
5	33	-0.037	0.0167	16	14	0.000	0.0653
13	25	0.0319	0.0112	34	36	-0.2149	0.0143
7	6	0.000	0.0259	16	15	0.3037	0.0842
26	27	0.2051	-0.3191	35	36	-0.2126	0.1166
28	7	-0.0211	0.0177	17	16	0.0305	0.1985
27	8	0.1546	0.0046	18	16	-0.082	0.0475
8	29	0.3273	0.1057	36	37	0.9958	0.0446
9	28	0.008	0.032	17	37	1.0094	0.3121
8	30	-0.0186	0.2178	19	18	0.0067	0.0323
10	28	0.000	0.0675	20	18	-0.0223	0.0053
8	31	3.1065	0.1309	38	19	0.7395	0.1094
11	28	0.0717	0.159	39	20	0.0525	0.547
9	30	0.1385	0.0884				

TABLE X
THE PROPOSED OF'S COEFFICIENTS IN THE THIRD SCENARIO

Coefficient	Value
a_1	0.52
a_2	0.07
a_3	0.07
a_4	0.3

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TABLE XI
TSM AND PSM FOR THE RELAYS IN THE THIRD SCENARIO

Relay No.	DE		IPM-GA		IPM-DE		IPM-BBM		IPM-IPM		Proposed Method	
	TSM	PSM	TSM	PSM	TSM	PSM	TSM	PSM	TSM	PSM	TSM	PSM
1	0.1061	2	0.1019	2	0.102	2	0.1019	2	0.1019	2	0.102	2
2	0.1001	1.75	0.1102	1.25	0.1001	1.5	0.1	1.5	0.1081	1.25	0.1079	1.25
3	0.1499	1.5	0.1443	1.5	0.1331	1.75	0.1313	1.75	0.1314	1.75	0.131	1.75
4	0.1	0.5	0.1	0.5	0.1001	0.5	0.1	0.5	0.1	0.5	0.1	0.5
5	0.1	2	0.1092	1.75	0.1001	2	0.1	2	0.107	1.75	0.1069	1.75
6	0.1008	2	0.1098	1.75	0.1	2	0.1	2	0.1	2	0.1	2
7	0.1124	2	0.1208	1.75	0.1123	2	0.1074	2	0.1076	2	0.1075	2
8	0.218	0.75	0.1921	1	0.1736	1.25	0.1734	1.25	0.1741	1.25	0.1686	1.25
9	0.1001	1.75	0.1	1.5	0.1001	1.5	0.1	1.5	0.1	1.5	0.1	1.5
10	0.1001	1.75	0.1082	1.25	0.1	1.5	0.1054	1.25	0.1055	1.25	0.1046	1.25
11	0.102	1.25	0.1037	1.25	0.1	1.5	0.1015	1.25	0.1015	1.25	0.1014	1.25
12	0.1001	1.5	0.1022	1.25	0.1	1.5	0.1	1.5	0.1022	1.25	0.1022	1.25
13	0.1109	2	0.1095	2	0.1088	2	0.1087	2	0.1089	2	0.1072	2
14	0.1242	2	0.1213	2	0.1196	2	0.1195	2	0.1199	2	0.1198	2
15	0.1227	2	0.1604	1.25	0.1435	1.5	0.1434	1.5	0.157	1.25	0.1571	1.25
16	0.1508	2	0.1579	1.75	0.1507	2	0.1507	2	0.1444	2	0.1443	2
17	0.1001	1.5	0.1068	1.25	0.1	1.5	0.1	1.25	0.106	1.25	0.1059	1.25
18	0.1314	2	0.129	2	0.1277	2	0.1277	2	0.1279	2	0.1251	2
19	0.1001	2	0.1	2	0.1	2	0.1	2	0.1024	1.75	0.1024	1.75
20	0.1229	2	0.1279	1.75	0.1181	2	0.1181	2	0.1167	2	0.116	2
21	0.1168	2	0.1275	1.75	0.1146	2	0.1146	2	0.1147	2	0.1129	2
22	0.1378	1.5	0.1401	1.5	0.1257	1.75	0.1257	1.75	0.1371	1.5	0.1371	1.5
$\sum_{i=1}^{22} t_{op,i}$	7.8086		7.7024		7.6499		7.5487		7.5482		7.5059	

TABLE VIII
PSM, TSM, OT, AND THE COEFFICIENTS OF CHARACTERISTIC CURVES FOR THE RELAYS IN THE SECOND SCENARIO

Relay	Proposed Method in [6]						Proposed Method					
	PSM (A)	TSM (s)	OT (s)	A	B	C	PSM (A)	TSM (s)	OT (s)	A	B	C
1	132.5025	1.36	0.0006	146.663	2.686	0.870	176.67	1.71	0.0861	93.451	1.681	0.686
2	617.565	1.26	0.0555	112.9513	2.494	0.274	308.7825	0.55	0.0742	126.397	1.782	0.520
3	128.7975	1.6	0.223	110.380	1.421	0.786	85.865	0.7	0.1965	140.753	1.218	0.683
4	86.19	0.57	0.8413	146.494	1.143	0.594	129.285	0.68	0.2081	87.38	1.561	0.576
5	136.37	0.58	0.1132	134.480	1.574	0.424	204.555	1.6	0.105	65.981	1.846	0.880
6	78.65	1.13	0.23	60.067	1.477	0.572	78.65	0.75	0.2956	112.808	1.469	0.549
7	242.19	0.19	0.17	161.448	2.158	0.654	80.73	0.81	0.2473	141.692	1.751	0.721
8	106.145	0.72	0.2361	154.027	1.300	0.263	212.29	0.15	0.0754	80.971	1.259	0.352
9	188.5	0.88	0.078	117.491	1.762	0.438	150.8	1.23	0.2039	150.386	1.583	0.807
10	406.64	1.64	0.0873	156.923	2.342	0.257	406.64	0.97	0.1683	74.022	1.776	0.632
11	290.355	1.91	0.0148	30.168	2.192	0.804	145.1775	1.51	0.0774	94.721	1.684	0.725
12	76.635	1.4	0.1702	177.417	1.671	0.555	25.545	0.24	0.3001	76.325	0.755	0.480
13	159.25	1.31	0.2277	127.341	1.651	0.502	191.1	1.77	0.079	152.593	2.133	0.450
14	214.695	1.61	0.0479	73.513	2.158	0.329	107.3475	0.65	0.1295	142.629	1.524	0.872
15	72.735	1.59	0.2092	55.905	1.520	0.409	36.3675	0.1	0.2304	185.738	0.940	0.484
16	78.39	1.99	0.0409	142.473	2.051	0.183	52.26	0.83	0.1338	79.300	1.314	0.480
17	47.645	0.99	0.0002	33.902	2.600	0.782	95.29	0.54	0.0077	158.459	2.371	0.481
18	106.73	0.76	0.1123	105.893	2.080	0.654	53.365	0.44	0.1583	129.673	1.528	0.721
19	178.1	0.69	0.0119	133.683	2.656	0.309	71.24	0.57	0.0262	55.257	1.655	0.901
20	202.3125	0.09	0.0412	49.079	1.443	0.366	242.775	0.38	0.0534	76.137	2.057	0.635
21	411.71	0.11	0.059	65.484	1.997	0.756	205.855	0.52	0.0392	81.257	2.252	0.724
22	257.595	0.1	0.0581	41.207	1.621	0.922	128.7975	0.3	0.1025	84.705	1.656	0.224
23	18.655	1.46	0.001	80.999	1.904	0.553	18.655	0.89	0.003	96.904	1.666	0.699
24	129.285	1.97	0.021	67.859	2.202	0.879	86.19	0.33	0.1375	107.311	1.267	0.372
25	170.4625	0.42	0.1831	47.660	1.707	0.338	68.185	0.5	0.1155	125.421	1.717	0.320
26	78.65	0.8	0.272	35.323	1.210	0.442	31.46	0.27	0.2209	99.245	1.009	0.494
27	121.095	0.64	0.5036	163.633	1.479	0.365	242.19	1.53	0.0594	100.654	2.696	0.315
28	159.2175	0.85	0.0577	55.035	2.503	0.611	159.2175	0.34	0.1055	116.185	2.215	0.601
29	113.1	0.99	0.4981	66.605	1.523	0.408	226.2	0.27	0.2603	28.307	1.348	0.325
30	203.32	0.07	0.0231	126.149	1.970	0.381	609.96	0.02	0.0716	30.751	1.147	0.446
31	145.1775	0.68	0.0175	133.539	2.217	0.354	96.785	0.14	0.0141	39.012	1.397	0.293
32	51.09	0.64	0.0876	155.327	1.521	0.555	51.09	1.57	0.2025	137.808	1.508	0.498
33	159.25	0.9	0.0722	171.593	2.769	0.553	191.1	0.14	0.1364	88.395	1.746	0.821
34	107.3475	1.47	0.0595	124.748	2.307	0.789	71.565	1.35	0.2125	46.133	1.461	0.519
35	60.6125	1.3	0.0572	63.561	1.631	0.823	36.3675	1.33	0.1104	173.371	1.537	0.597
36	78.39	2	0.0123	71.251	2.745	0.433	26.13	0.18	0.2747	98.770	0.927	0.637
37	133.4125	1.82	0.5934	139.721	1.860	0.580	53.365	0.41	0.318	164.784	1.284	0.260
38	80.925	1.18	0.0589	62.856	2.862	0.235	80.925	0.38	0.1068	21.859	1.749	0.728
39	42.51	0.26	0.0215	94.203	2.009	0.722	42.51	0.43	0.0398	117.436	2.040	0.485
Sum		39.93	5.5681					27.08	5.3868			