Considering Different Network Topologies in Optimal Overcurrent Relay Coordination Using a Hybrid GA

Abbas Saberi Noghabi, Javad Sadeh, *Member, IEEE*, and Habib Rajabi Mashhadi, *Member, IEEE*

***Abstract*—The directional overcurrent relays (DOCRs) coordination problem is usually studied based on a fixed network topology in an interconnected power system, and is formulated as an optimization problem. In practice, the system may be operated in different topologies due to outage of the transmission lines, transformers, and generating units. There are some situations for which the changes in the network topology of a system could cause the protective system to operate without selectivity. The aim of this paper is to study DOCRs coordination considering the effects of the different network topologies in the optimization problem. Corresponding to each network topology, a large number of coordination constraints should be taken into account in the problem formulation. In this situation, in addition to nonlinearity and nonconvexity, the optimization problem experiences many coordination constraints. The genetic algorithm (GA) is selected as a powerful tool in solving this complex and nonconvex optimization problem. In this paper, in order to improve the convergence of the GA, a new hybrid method is introduced. The results show a robust and optimal solution can be efficiently obtained by implementing the proposed hybrid GA method.**

***Index Terms*—Different network topologies, genetic algorithm (GA), overcurrent relay coordination, power system protection.**

I. Introduction

THE MAIN function of protective relays on power system is to detect and remove the faulted parts as fast and selectively as possible. Directional overcurrent relays (DOCRs) have been commonly used as an economic alternative for the protection of subtransmission and distribution system or as a secondary protection of transmission system. DOCRs have two types of settings: pickup current setting ($I_{\rm set}$) and time multiplier setting (TMS). Basically, to determine these settings, two different approaches are used; conventional approach, and optimization techniques. The basis of the conventional protection approach is the concept of predeterminism (i.e., analysis of all faults, abnormal operating conditions, and system contingencies are predetermined) [1], [2].

The optimization techniques simplify the conventional approach and because of the inherent advantages, it gains popularity. In contrast to the conventional approach, in optimization-based methods, it does not need to determine breakpoint set usually obtained via a complex computation procedure [3].

Several optimization techniques have been proposed to solve the overcurrent relay coordination problem [4]–[13]. Mathematically, DOCRs coordination problem is a mixed integer nonlinear programming (MINLP) where the $I_{\rm set}$ parameters are considered as integer variables and the TMS parameters are continuous. In [4], the relay coordination problem is formulated as an MINLP problem and is solved using GAMS software. Due to the complexity of the MINLP technique, the coordination of overcurrent relays is commonly performed by linear programming (LP) techniques, such as Simplex, dual Simplex, and two-phase Simplex methods [5]–[9]. In these methods, pickup current settings are assumed to be known and the operation time of each relay is considered as a linear function of its TMS. Recently, intelligence based optimization methods are applied to solve the DOCRs coordination problem as a complex and non-convex optimization problem. In [10]–[13], genetic algorithm (GA), evolutionary algorithm (EA), and particle swarm optimization (PSO) algorithms are proposed to calculate the optimal solution for relay settings. Considering the nonlinearity effects and handling, integer variables in problem formulation are the main advantages of the intelligent methods.

The network topology frequently changes due to various operating conditions and occurring system contingencies. These changes in the network topology could cause the protective system to operate without selectivity. The relays will operate correctly if the effects of these changes are taken into account when solving the relay coordination problem. So far, almost all of the proposed methods are designed to coordinate the overcurrent relays based on fixed network topology. In practice, the system experiences different topologies regarding to single contingencies. Corresponding to each network topology, there is a set of nonlinear inequality constraints. The aim of this paper is to find an optimal solution for the DOCRs coordination problem such that large number of coordination constraints related to the different network topologies are simultaneously satisfied. In this situation, the DOCRs coordination problem is a complex and nonconvex optimization problem with many nonlinear constraints. A novel hybrid GA method is developed and used to determine the optimal relay settings. The hybrid GA method is designed to improve the convergence of conventional GA using a local LP optimizer. In the proposed hybrid method, only the pickup current settings of all relays are coded into genetic string as discrete variables. The LP is used to calculate the optimal TMS of relays as continuous variables for each genetic string.

II. Relay Coordination Problem

In the coordination problem of DOCRs, the aim is to determine the time multiplier setting and pickup current setting of each relay, so that the overall operating time of the primary re-

Manuscript received September 22, 2008; revised January 12, 2009. Current version published September 23, 2009. Paper no. TPWRD-00727-2008.

The authors are with the Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran (e-mail: ab_sa82@stu-mail.um.ac.ir; sadeh@um.ac.ir; h_mashhadi@um.ac.ir).

Digital Object Identifier 10.1109/TPWRD.2009.2029057

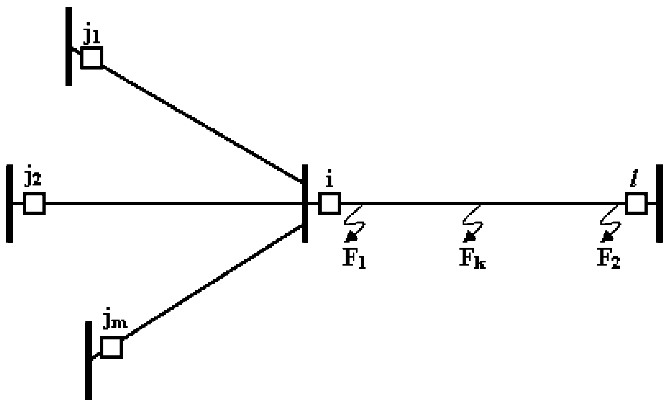

Fig. 1. Primary and backup relays.

lays is minimized [4]. Therefore, the objective function can be defined as follows:

$$\min\ J=\sum_{i=1}^{n} w_i t_i \tag{1}$$

where n is the number of relays and t_i is the operating time of the ith relay for near-end fault. In Fig. 1, the near-end fault and the far-end fault for ith relay are shown as F_1 and F_2 respectively. The weight w_i depends upon the probability of a given fault occurring in each protection zone and is usually set to one [4].

A. Relay Characteristics

Different linear and nonlinear overcurrent relay characteristics are reported in the literature. Without loss of generality, in this paper, the following nonlinear and popular characteristics function based on IEC standard is considered:

$$t_i=\frac{0.14\times \mathrm{TMS}_i}{\left(\frac{I_i}{I_{\mathrm{set}_i}}\right)^{0.04}-1} \tag{2}$$

where TMS_i and I_{set_i} are the time multiplier setting and pickup current setting of the ith relay, respectively and I_i is the fault current passing through ith relay. It can be seen from (2) that the nonlinearity in relay characteristics function is related to pickup current variable. If the parameter I_{set} is assumed to be determined prior, then the relay characteristics will be a linear function of TMS variable. In this case, the coordination problem can be formulated as a linear programming problem.

The coordination constraints can be formulated as follows:

B. Primary-Backup Relay Constraints

The coordination constraints between the primary relay i and its/their backup relay(s) j for the near-end and the far-end faults are: (see Fig. 1)

$$t_j^{F_1}-t_i^{F_1}\geq \mathrm{CTI} \tag{3}$$
$$t_j^{F_2}-t_i^{F_2}\geq \mathrm{CTI} \tag{4}$$

where $t_i^{F_1}$ and $t_i^{F_2}$ are the operating time of ith primary relay for the near-end and far-end faults respectively. Also, $t_j^{F_1}$ and $t_j^{F_2}$ are defined in the same way as the jth backup relay respectively. The Coordination Time Interval (CTI) is the minimum interval that permits the backup relay to clear a fault in its operating zone. In other words, the CTI is the time lag in operation between the primary and its backup relay. It includes many factors, such as the breaker operating time, relay overtravel time and a safety margin. The value of CTI is usually selected between 0.2 and 0.5 s.

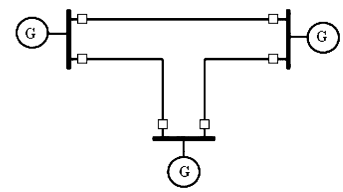

Fig. 2. Three-bus system.

C. Bounds on the Relay Settings

The limits on the relay parameters can be presented as follows:

$$\mathrm{TMS}_i^{\min}\leq \mathrm{TMS}_i\leq \mathrm{TMS}_i^{\max} \tag{5}$$
$$\max\left(I_{\mathrm{load}_i}^{\max}, I_{\mathrm{set}_i}^{\min}\right)\leq I_{\mathrm{set}_i}\leq \min\left(I_{\mathrm{fault}_i}^{\min}, I_{\mathrm{set}_i}^{\max}\right). \tag{6}$$

The minimum pickup current setting of the relay is the maximum value between the minimum available tap settings $(I_{\mathrm{set}}^{\min})$ on the relay and maximum load current $(I_{\mathrm{load}}^{\max})$ passes through it. In similar, the maximum pickup current setting is chosen less than the minimum value between the maximum available tap settings $(I_{\mathrm{set}}^{\max})$ on the relay and minimum fault current $(I_{\mathrm{fault}}^{\min})$ which passes through it.

D. Multiple Network Topology Constraints

Almost all of the proposed methods in coordination problem coordinate the overcuurent relays based on fixed network topology (i.e., main topology). However, the network topology may change due to maintenance activities, transmission network reconfigurations and switching actions after faults or load level changes. These changes in the network topology can lead to miscoordination of directional overcurrent relays. To overcome this drawback, in this paper different network topologies are considered in problem formulation. The coordination constraints between the primary relay i and its/their backup relay(s) (j_1, j_2, j_3), in Fig. 1, considering different network topologies are given by

$$\left(t_j^{F_1}\right)^s-\left(t_i^{F_1}\right)^s\geq \mathrm{CTI}\quad s\in S \tag{7}$$
$$\left(t_j^{F_2}\right)^s-\left(t_i^{F_2}\right)^s\geq \mathrm{CTI}\quad s\in S \tag{8}$$

where S is a set of all topologies which obtained under single line outage contingencies of the main topology. For example, Fig. 2 illustrates a three bus system, and three topologies based on single line outage of this network are shown in Fig. 3. These entire topologies along with main topology are considered in coordination constraints, as (7) and (8).

III. Conventional Genetic Algorithm Method

In mathematical terms, DOCRs coordination is a mixed integer nonlinear programming problem. This complex and non-

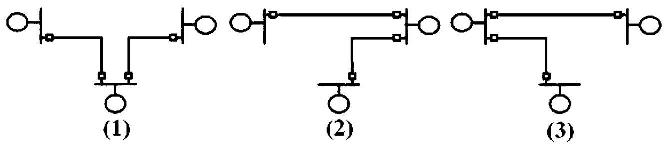

Fig. 3. Three network topologies of three-bus system.

$I_{set\ 1}$		$I_{set\ n}$	TMS_1		TMS_n
	...			...	

Fig. 4. Structure of the chromosome in the conventional GA method.

convex optimization problem should be solved considering a large number of different linear and nonlinear inequality constraints. These days, GA is used as a powerful tool in optimization problems, especially in the nonconvex optimization problems [14].

The decision variables in the GA are usually encoded into binary string as a set of genes corresponding to chromosomes in biological systems. A group of the chromosomes are called a population. The GA is essentially a method to generate a new population or generation from a given population. Members of each generation are ranked according to a specific criterion called fitness which is derived from the objective function and constraints of optimization problem. In each generation, the genetic operators (i.e., selection, crossover, and mutation) are applied to the individuals in the current population [14], [17].

In the DOCRs coordination problem, the decision variables are the TMS and $I_{\rm set}$ variables for each relay. Therefore, in the conventional GA method a chromosome is defined in the form of a genetic string which contains both TMS and $I_{\rm set}$ parameters as discrete variables. Fig. 4 shows structure of the chromosome when the network consists of n overcurrent relays.

To solve the DOCRs optimization problem, it is assumed the problem has a non-empty feasible set. However, the genetic algorithm as a powerful method is able to search the decision space from a set of feasible and non-feasible solutions and converge to the global optimum. To satisfy the constraints and find feasible solutions, the mechanism of fitness function evaluation should be properly designed. To achieve this goal, the fitness value is penalized when a solution violates some of the constraints. Thus, the GA is led to the feasible region of the decision space. However, if the main problem does not have a feasible solution set, the GA can find a solution which has minimum number of violated constraints.

IV. Proposed Hybrid GA and LP Method

To increase the computational efficiency of GA, as reported in many research works [15]–[17], it is beneficial to hybridize GA with conventional optimization methods. In this research work, using LP method, a new hybrid technique is presented and applied to DOCRs coordination problem.

The basic idea is the decomposition of the studied coordination problem in two subproblems. The GA is used to solve the first subproblem [i.e., the nonlinear part of optimization problem (1)] in order to determine the $I_{\rm set}$ variables. Thus, each chromosome in the genetic population presents only the $I_{\rm set}$ variables

$I_{set\ 1}$		$I_{set\ n}$
	...	

Fig. 5. Structure of chromosome in the hybrid GA method.

as shown in Fig. 5. By extracting the chromosome information, the DOCRs coordination problem is converted to a Linear Programming problem. Therefore to evaluate the fitness value for each chromosome, the standard LP is solved to determine the corresponding TMS variables.

Due to decreasing the length of the genetic string in the proposed method, the GA's search space is significantly reduced. As an example, consider a system consist of 14 overcurrent relays. Suppose each relay has 8 available tap setting points and 16 available time multiplier setting points. In conventional GA methods based on Fig. 4, the GA's search space has $8^{14} \times 16^{14}$ states. But total states of GA's search space in the proposed hybrid GA method based on Fig. 5 are limited to 8^{14} states.

The flowchart of the proposed hybrid GA is shown in Fig. 6. At first, for each network topology the Primary/Backup (P/B) relay pairs are identified using graph theory. After that, for each P/B relay pairs corresponding to the studied topology, the short circuit currents passing through the relays for near- and far-end faults are calculated.

The main part of this flowchart which is related to the optimization procedure is explained in two blocks as follows:

a) **Genetic Algorithm Process**: In the first step of GA, the initial population is created randomly. The initial $\rm I_{set}$ variable corresponding to each relay is randomly selected based on the mentioned interval that introduced in (6). The next step is evaluation of fitness value for each chromosome in the current generation. The fitness value is defined based on the objective function in (1) which is the overall operating time of primary relays. To evolve the current population and reach to optimal solution, proportional to fitness value, the GA selects some chromosome and uses them for producing the next generation. In order to generate new individuals in the decision space, the crossover and mutation operators are applied to the pair of selected chromosomes. The process will be terminated after a fixed number of generations. The required number of generations varies from system to system and it depends on the system complexity and size of the genetic population.

b) **LP Subproblem**: As Fig. 6 shows, the LP subproblem is the main part of fitness function evaluation which is called several times by the GA process. To compute the fitness value for each chromosome, at first the values of the $\rm I_{set}$ variables are extracted by decoding the chromosome information. Based on the fixed values of the $\rm I_{set}$ variables, the nonlinear DOCRS coordination problem is converted to a LP problem. After that, by solving this LP problem the corresponding fitness value and the TMS variables are computed. For some individuals according to the values of the $\rm I_{set}$ variables, the LP subproblem is not converged. In these cases, some of the inequality coordination constraints are violated. To decrease the chance of these chromosomes in the selection process, their fitness values are penalized. The amount of penalty is composed of a fixed

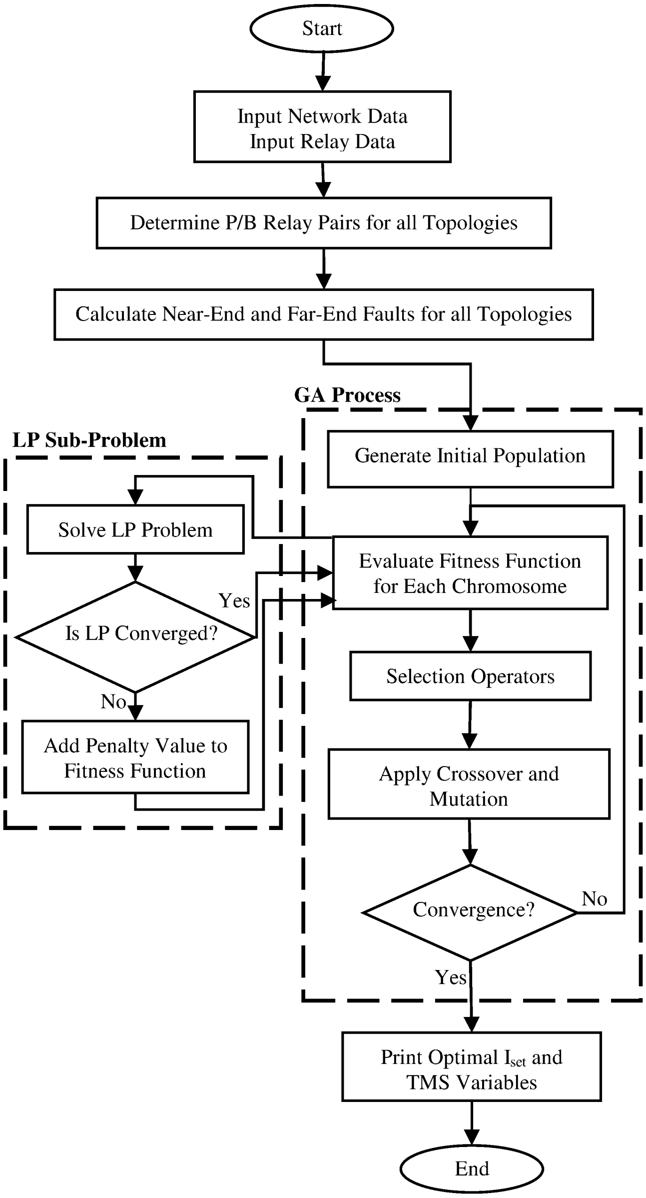

Fig. 6. Flowchart of proposed hybrid GA method.

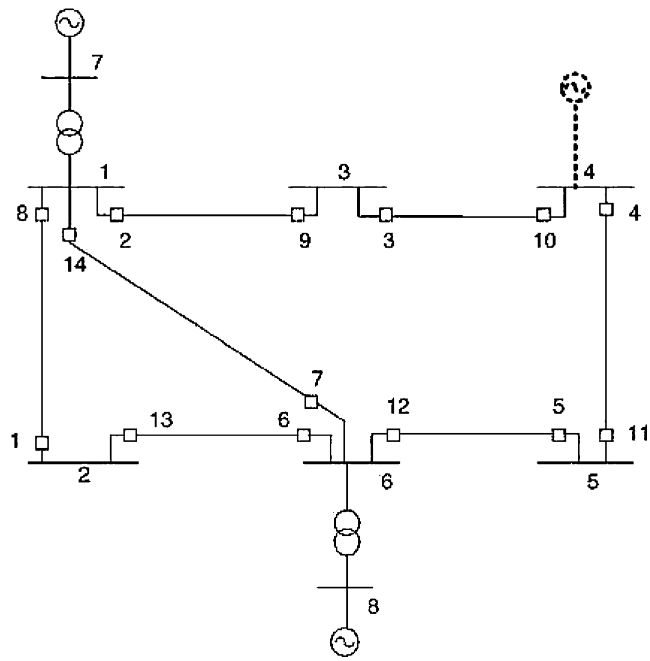

Fig. 7. Single line diagram of 8-bus system.

TABLE I
CT RATIO

Relay no.	CT ratio
1	240
2	240
3	160
4	240
5	240
6	240
7	160
8	240
9	160
10	240
11	240
12	240
13	240
14	160

value and a variable value in proportion to the number of violated constraints.

V. CASE STUDY

The proposed method is applied to an 8-bus, 9-branch network shown in Fig. 7. The system data is given in [12]. At bus 4, there is a link to another network, modeled by a short circuit capacity of 400 MVA. The transmission network consists of 14 relays which their location are indicated in Fig. 7. The same inverse time characteristic is considered for all of these relays [i.e., (2)]. The TMS values can range continuously from 0.1 to 1.1, while seven available discrete pickup tap settings (0.5, 0.6, 0.8, 1.0, 1.5, 2.0 and 2.5) are considered [12]. The ratios of the current transformers (CTs) are indicated in Table I and CTI is assumed to be 0.3 seconds.

Table II shows the primary/backup (P/B) relay pairs and corresponding fault currents passing through them for the studied system. Obviously, when the system topology is changed the presented data in Table II should be updated.

A. Fixed Network Topology

In this subsection considering the fixed network topology formulation, the DOCRs coordination problem is solved using the conventional GA and the proposed hybrid method.

To have better convergence, different population sizes and different maximum number of iterations are examined. Fig. 8 shows the fitness value of the best individual in the population with respect to the number of generations for both methods. The population size is assumed to be 100 individuals. It is noticed that the both methods successfully converge to the approximately the same value. However, the convergence rate of the hybrid GA method is very fast, reaching to its optimal value in less than 30 iterations, while the convergence of the conventional GA method requires at least 100 000 iterations. It can be seen from Fig. 8 that the fitness value of best individual

TABLE II
P/B RELAY PAIRS AND THE FAULT CURRENTS IN THE MAIN NETWORK TOPOLOGY

P/B pairs		Near-End Fault Currents(kA)	
Primary Relay No.	Backup Relay No.	Primary Relay	Backup Relay
1	6	3.232	3.232
2	1	5.924	0.996
2	7	5.924	1.890
3	2	3.556	3.556
4	3	3.783	2.244
5	4	2.401	2.401
6	5	6.109	1.197
6	14	6.109	1.874
7	5	5.223	1.197
7	13	5.223	0.987
8	7	6.093	1.890
8	9	6.093	1.165
9	10	2.484	2.484
10	11	3.883	2.344
11	12	3.707	3.707
12	13	5.899	0.987
12	14	5.899	1.874
13	8	2.991	2.991
14	1	5.199	0.996
14	9	5.199	1.165

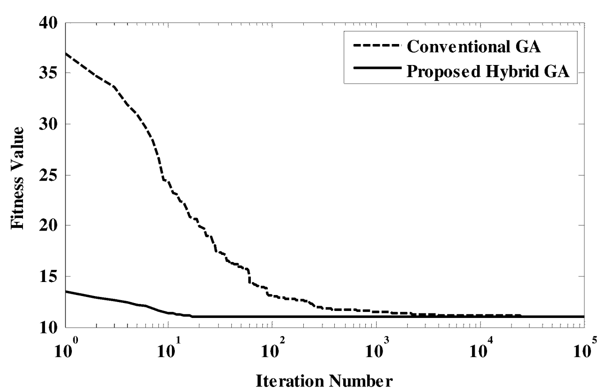

Fig. 8. Convergence of the proposed hybrid GA and the conventional GA considering the fixed network topology.

corresponding to the conventional GA method has a large value during the first iterations. This is because some coordination constraints are violated and therefore the fitness values are penalized.

To analyze the sensitivity of the proposed method with respect to initial population, different random initial populations are examined. It is seen in Fig. 9 that the proposed method is able to find the optimal solution for all cases in less than 30 iterations. Thus the convergence of the proposed hybrid GA method is not significantly affected by the initial population.

Table III clearly shows the advantages of the proposed method in comparison with the conventional GA. The reduction of chromosome length in the hybrid GA method is the main reason for the differences between the presented results. In other words, in the proposed method the GA is used to determine only pickup tap setting variables and the TMS variables are efficiently computed by the local LP optimizer. Thus the GA's search space is reduced drastically. Consequently, the computational time and iteration numbers in the hybrid GA method are significantly improved, as shown in Table III.

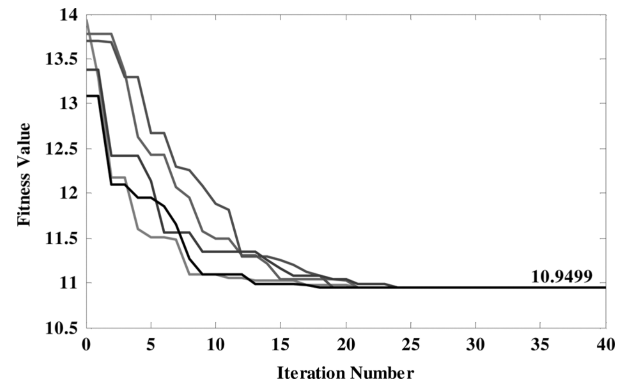

Fig. 9. Convergence of the proposed method for five different random initial populations considering the fixed network topology.

TABLE III
COMPARISON BETWEEN THE PROPOSED METHOD AND THE CONVENTIONAL GA METHOD

Methods	Hybrid GA	Conventional GA
Chromosome Length	42 bits	140 bits
GA's Search Space	7^{14}	7^{14}x100^{14}
Computational Time (Pentium IV CPU 3.0GHz)	5 minutes	600 minutes
Iteration Number	30	100000

The optimal values of the decision parameters (i.e., pickup tap settings and TMS variables) for both methods are shown in Table IV. It can be seen from the results presented in this table that, the TMS variables and the optimal value of objective function are approximately the same, whereas the pickup tap settings are completely the same. It is important to note that in the conventional GA method the TMS variables are coded as discrete ones with step size of 0.01, but in the proposed method these are considered as continuous variables.

Generally, the changes in network topology may cause the protective system to operate without selectivity. For example, if the line between buses 1 and 2 is removed, the short-circuit capacity of the buses and consequently the operation time of the primary and backup relays are changed. Table V shows the results of operating time for near-end faults, when the relay settings calculated based on the fixed network topology as depicted in fourth and fifth columns of Table IV.

The operating time of backup and primary relays (t_j and t_i) are shown in columns 2 and 4 of Table V, respectively. Furthermore, the "constraint value" is defined in (9) and computed for each coordination constraint

$$\text{constraint value} = t_j - t_i - \text{CTI}. \quad (9)$$

The last column of this table shows the "constraint value" based on (9) where the negative values indicate violation of the associated constraints. So, it is seen that the removal of the line between buses 1 and 2 results in violation of nine coordination constraints.

TABLE IV
THE RESULTS OF THE PROPOSED AND THE CONVENTIONAL GA METHODS IN THE FIXED NETWORK TOPOLOGY

Relay No.	Conventional method		Proposed method	
	Pick up Tap	*TMS*	Pick up Tap	*TMS*
1	1.0000	0.29	1.0000	0.3043
2	2.5000	0.31	2.5000	0.2917
3	2.5000	0.26	2.5000	0.2543
4	2.5000	0.19	2.5000	0.1851
5	1.5000	0.18	1.5000	0.1700
6	2.5000	0.26	2.5000	0.2711
7	0.5000	0.54	0.5000	0.5316
8	2.5000	0.24	2.5000	0.2387
9	2.0000	0.17	2.0000	0.1865
10	2.5000	0.19	2.5000	0.1895
11	2.5000	0.21	2.5000	0.2014
12	2.5000	0.30	2.5000	0.2890
13	1.5000	0.23	1.5000	0.2207
14	0.5000	0.51	0.5000	0.5278
Obj_Fun	11.0010		10.9499	

TABLE V
THE RELAYS OPERATION TIME FOR NEAR-END FAULTS AFTER REMOVING LINE BETWEEN BUSES 1 AND 2

Backup Relay		Primary Relay		Constraint Value
Relay No.	Operation Times(sec)	Relay No.	Operation Times(sec)	
2	1.121	3	0.817	0.005
3	1.017	4	0.718	**-0.002**
4	0.948	5	0.659	**-0.011**
5	1.033	6	0.768	**-0.035**
5	1.033	7	0.923	**-0.19**
7	1.069	2	0.890	**-0.121**
9	1.036	14	0.914	**-0.178**
10	0.956	9	0.664	**-0.009**
11	1.031	10	0.664	0.067
12	1.088	11	0.784	0.004
14	1.057	6	0.768	**-0.011**
14	1.057	12	0.884	**-0.127**

B. Multiple Network Topologies

In order to avoid the violation of the coordination constraints, in this subsection the conventional GA and the proposed hybrid method are applied to solve the DOCRs coordination problem considering multiple network topologies. The fitness value of the best individual in the population with respect to the number of generations for both methods is shown in Fig. 10.

It is observed from Fig. 10 that the conventional GA method exhibits poor convergence. The main reason for poor convergence of the conventional GA in this case is due to increasing the number of coordination constraints. As indicated in Fig. 10 after about 100 000 generations, the fitness value for the conventional GA reaches to 112.43 seconds which is the sum of overall operating time and penalty values related to six violated coordination constraints. However, the proposed method is converged to the optimal and feasible solution in less than 50 iterations. The optimal value of the objective function is equal to 19.3476 seconds and all of the constraints are satisfied. Fig. 11 shows, similar to the previous case, the convergence of the proposed method is insensitive to initial population.

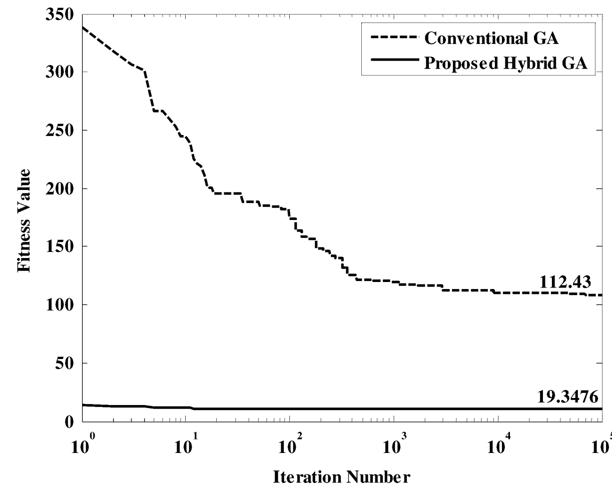

Fig. 10. Convergence of the proposed hybrid GA and the conventional GA considering multiple network topologies.

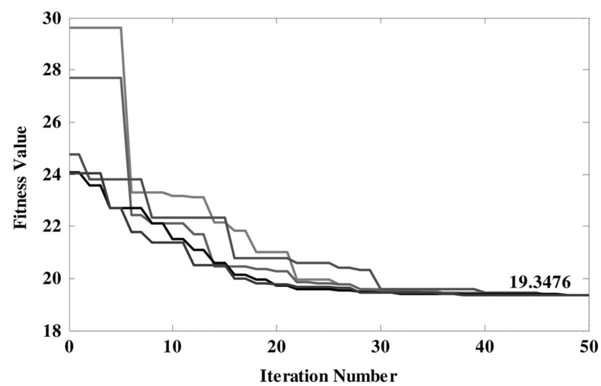

Fig. 11. Convergence of the proposed method for five different random initial populations considering different network topologies.

Therefore, the capability of the proposed method to find the optimal solution is the salient advantage of this method over the conventional GA method. The optimal values of the decision variables considering multiple network topologies using the proposed hybrid GA method are given in Table VI.

The results in Tables IV and VI show that the optimal value of the objective function increases to 19.3476 sin the case of multiple network topologies, as compare to the value of 10.9499 s when considering just the main topology. Furthermore, the TMS variables of the relays are increased in the case of multiple network topologies. However, the protective system will be robust against changes in the network topology.

VI. CONCLUSION

In this paper, a new formulation for the DOCRs coordination problem considering different network topologies is presented. The main contribution of this research work is introducing concept of *robust coordination*. In other words, the aim is to find an optimal solution for the coordination problem such that large number of coordination constraints corresponding to a set of network topologies are simultaneously satisfied. In this case, the DOCRs coordination problem is a complex optimization problem including many nonlinear constraints. A new hybrid GA method is proposed and successfully applied to solve this

TABLE VI
THE RESULTS CONSIDERING MULTIPLE NETWORK TOPOLOGIES

Relay No.	Pick up Tap	*TMS*
1	1.0000	0.5614
2	2.5000	0.4907
3	2.5000	0.4717
4	2.5000	0.3541
5	0.8000	0.5156
6	2.5000	0.4422
7	2.0000	0.5385
8	2.5000	0.4198
9	2.0000	0.3655
10	2.5000	0.3225
11	2.5000	0.3586
12	2.5000	0.4585
13	0.8000	0.5862
14	2.0000	0.5084
Obj_Fun	19.3476	

complex optimization problem. Due to decreasing the search space of GA and using LP as an efficient local optimizer, computational efficiency of the new proposed hybrid GA is significantly improved.

REFERENCES

[1] N. A. Laway and H. O. Gupta, "Adaptive coordination of directional overcurrent relays of electrical power systems using network decomposition approach," *J. Inst. Eng. (IEJ), India*, vol. 75, pp. 143–149, Nov. 1995.

[2] A. Y. Abdelaziz, H. E. A. Talaat, A. I. Nosseir, and A. Hajjar Ammar, "An adaptive protection scheme for optimal coordination of overcurrent relays," *Electr. Power Syst. Res.*, vol. 61, pp. 1–9, 2002.

[3] N. A. Laway and H. O. Gupta, "Coordination of directional relays without using topological analysis of power transmission systems," *IE (I) J. Electr., India*, pp. 190–193, 1994.

[4] A. J. Urdaneta, R. Nadira, and L. G. Perez, "Optimal coordination of directional overcurrent relays in interconnected power systems," *IEEE Trans. Power Del.*, vol. 3, no. 3, pp. 903–911, Jul. 1988.

[5] A. J. Urdaneta, H. Restrepo, S. Marquez, and J. Sanchez, "Coordination of directional overcurrent relay timing using linear programming," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 122–129, Jan. 1996.

[6] B. Chattopadhyay, M. S. Sachdev, and T. S. Sidhu, "An online relay coordination algorithm for adaptive protection using linear programming technique," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 165–173, Jan. 1996.

[7] A. J. Urdaneta, L. G. Perez, and H. Restrepo, "Optimal coordination of directional overcurrent relays considering dynamic changes in the network topology," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1458–1464, Oct. 1997.

[8] A. J. Urdaneta, L. G. Pérez, J. F. Gómez, B. Feijoo, and M. González, "Presolve analysis and interior point solutions of the linear programming coordination problem of directional overcurrent relays," *Elect. Power Energy Syst.*, vol. 23, no. 8, pp. 819–825, Nov. 2001.

[9] H. K. Karegar, H. A. Abyaneh, V. Ohis, and M. Meshkin, "Pre-processing of the optimal coordination of overcurrent relays," *Electr. Power Syst. Res.*, vol. 75, pp. 134–141, Aug. 2005.

[10] C. W. So, K. K. Li, K. T. Lai, and K. Y. Fung, "Application of genetic algorithm for overcurrent relay coordination," in *Proc. Inst. Elect. Eng. Developments in Power System Protection Conf.*, 1997, pp. 66–69.

[11] C. W. So and K. K. Li, "Time coordination method for power system protection by evolutionary algorithm," *IEEE Trans. Ind. Appl.*, vol. 36, no. 5, pp. 1235–1240, Sep. 2000.

[12] H. H. Zeineldin, E. F. El-Saadany, and M. M. A. Salama, "Optimal coordination of overcurrent relays using a modified particle swarm optimization," *Elect. Power Syst. Res.*, vol. 76, pp. 988–995, 2006.

[13] M. M. Mansour, S. F. Mekhamer, and N. El-Sherif El-Kharbawe, "A modified particle swarm optimizer for the coordination of directional overcurrent relays," *IEEE Trans. Power Del.*, vol. 22, no. 3, pp. 1400–1410, Jul. 2007.

[14] D. A. Whitley, "A genetic algorithm tutorial," *J. Statist. Comput.*, vol. 4, pp. 65–85, 1994.

[15] D. E. Goldberg and S. Voessner, "Optimizing global-local search hybrids," 1999. [Online]. Available: http://www-IlliGal.ge.uiuc.edu

[16] H. Bersini, Hybridize, Hybridize and Hybridize Again Univ. Libre de Bruxelles, IRIDIA, Bruxelles, Belgium, Tech. rep., 1996.

[17] H. R. Mashhadi, H. M. Shanechi, and C. Lucas, "A new genetic algorithm with Lamarckian individual learning for generation scheduling," *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 1181–1186, Aug. 2003.

Abbas Saberi Noghabi was born in Gonabad, Iran, in 1977. He received the B.Sc. degree in electrical engineering from Abbaspour University, Tehran, Iran, in 1999, the M.Sc degree in electrical engineering from K. N. Toosi University of Technology, Tehran, in 2001, and is currently pursuing the Ph.D. degree at Ferdowsi University of Mashhad, Mashhad, Iran.

His research interests are power system protection and power system operation and optimization methods.

Javad Sadeh (M'08) was born in Mashhad, Iran, in 1968. He received the B.Sc. and M.Sc. degrees (Hons.) in electrical engineering from Ferdowsi University of Mashhad, Mashhad, Iran, in 1990 and 1994, respectively, and the Ph.D. degree in electrical engineering from Sharif University of Technology, Tehran, Iran with the collaboration of the Electrical Engineering Laboratory of the Institut National Polytechnique de Grenoble (INPG), Grenoble, France, in 2001.

Since then, he has been an Assistant Professor at the Ferdowsi University of Mashhad. His research interests are power system protection, dynamics, and operation.

Habib Rajabi Mashhadi (M'09) was born in Mashhad, Iran, in 1967. He received the B.Sc. and M.Sc. degrees (Hons.) in electrical engineering from the Ferdowsi University of Mashhad, Mashhad, and the Ph.D. degree in electrical and computer engineering from Tehran University, Tehran, Iran, under the joint cooperation of Aachen University of Technology, Aachen, Germany.

He is an Associate Professor of Electrical Engineering at Ferdowsi University. His research interests are power system operation and economics, power system planning, and biological computation.