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An Innovative Fast Relay Coordination Method to Bypass the Time Consumption of Optimization Algorithms in Relay Protection Coordination

Mostafa Kheshti*, Xiaoning Kang* and Zaibin Jiao†

Abstract – Relay coordination in power system is a complex problem and so far, meta-heuristic algorithms and other methods as an alternative approach may not properly deal with large scale relay coordination due to their huge time consuming computation. In some cases the relay coordination could be unachievable. As the urgency for a proper approach is essential, in this paper an innovative and simple relay coordination method is introduced that is able to be applied on optimization algorithms for relay protection coordination. The objective function equation of operating time of relays are divided into two separate functions with less constraints. As the analytical results show here, this equivalent method has a remarkable speed with high accuracy to coordinate directional relays. Two distribution systems including directional overcurrent relays are studied in DigSILENT software and the collected data are examined in MATLAB. The relay settings of this method are compared with particle swarm optimization and genetic algorithm. The analytical results show the correctness of this mathematical and practical approach. This fast coordination method has a proper velocity of convergence with low iteration that can be used in large scale systems in practice and also to provide a feasible solution for protection coordination in smart grids as online or offline protection coordination.

Keywords: Overcurrent relay, Relay coordination, Evolutionary algorithm, Fast coordination

1. Introduction

Relay protection is inevitably a vital part of power system and a proper coordination setting is one of the most essential requirements of protection schemes to reach the highest reliability. When a fault occurs, a desirable protection scheme must be able to remove the faulty portion of a system with least loss and isolate it from the healthy parts rapidly to provide maximum continuity of supply. To ensure the reliability of the protection, a pair of relays are coordinated, one as the primary (main) protection and the other as backup protection in such a way that if a fault occurs, the main relay must operate as quickly as possible to remove the faulty part. If due to some reasons the main protection fails to react, the backup protection needs to operate. Although a backup relay removes the fault from the system, but it also disconnects a bigger portion of the system including a healthy part hence minimizing the continuity of supply and increasing the power loss which is economically undesirable. The energy dissipation due to the heat will increase and damage the equipment. Besides, as a large number of relay trippings are because of incorrect or insufficient settings than due to genuine faults [1], need for a reliable and proper relay coordination scheme with optimum performance and quick computation process is urgent.

Majority of the power system includes meshed, ring and two way power flow where directional overcurrent relays (DOCRs) are a suitable and economical protection scheme. The protection design of DOCRs is based on two parameters, time multiplier setting (TMS) and plug setting (PS). Correct TMS and PS settings allow a protection engineer to coordinate relays in the system while fault can be cleared by primary relay as fast as possible. If the main relay fails to operate, the coordinated backup relay needs to operate immediately after a time interval and not specifically before primary relay. TMS and PS setting of each relay must be coordinated with other backup relays, where again relays act with different current settings which makes the coordination, a very complex task. Each two relays include 4 variables (TMS, PS) and the complexity of coordination will be intense in bigger systems with more relays and constraints.

Different solutions have been studied to address this complex issue such as simplex method [2,3], graphical selection procedure [4], and application of several optimization algorithms which among them, particle swarm optimization (PSO)[5-9], bee colony algorithm (BCA)[10], genetic algorithm (GA)[11,12], differential

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† Corresponding Author: State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, China. (jiaozaibin@mail.xjtu.edu.cn)
* State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, China. (kheshti@ieee.org, kangxn@mail.xjtu.edu.cn)

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evolution (DE) method [13], ant colony optimization (ACO)[14] and etc., have been presented. Although these methods have been investigated for relay coordination issue, in a medium and large scale power system the application of such methods are quite time consuming [15] and in some cases completely difficult and due to this reason meta-heuristic algorithms are not able to sufficiently and quickly process the coordination in practice. In a future smart grid where the relays need to operate efficiently and correctly based on their settings and flexible situation of the grid, protection coordination would be a nightmare challenge. Evolutionary algorithms could be a solution but their improper calculation time and inefficient results without reaching global values have kept the situation undesirable.

Therefore, to overcome the tremendous and improper time consumption problem of meta-heuristic algorithms and provide a feasible solution to present systems and future smart grids, this paper presents a very innovative and simple approach of coordination for directional relays which has a quite fast calculation process that can be used in practice and simply in smart grids with two way power flow. The proposed method can be applied on any intelligent algorithm for relay protection studies. Besides, as a patch for evolutionary algorithms, this method can help to reach the global values in an optimization process.

The relay coordination problem is formulated by operation time objective function subject to some constraints. In this paper, the operation time of all relays in a system are formulated in an objective function. Then, this objective is divided into two separate functions. This separation reduces the complexity and dimension of the constraints associated with the objective functions. These two functions are optimized separately subject to the reduced constraints. This proposed technique is applied on two case study systems to verify the effectiveness of this method. The first case study system has 12 DOCRs and the second system has 24 DOCRs. The power flow and fault analysis of these test systems are performed in DigSILENT software and the data analysis is run in MATLAB software. The objective functions are solved using the proposed technique. The results are compared with PSO and GA. The obtained results confirm that if the objective function is divided into two separate functions, the problem can be solved easier and consequently, the relay protection scheme has much better performance. Also, it can alleviate the computational burden on the relay coordination. In large scale power system, the relay coordination is extremely complex and solving such problems require huge computations. Application of the proposed fast coordination method can reduce the computations dramatically and allow the relay coordination to be solved with better quality of solution and faster speed. The optimization algorithms can also perform with better convergence and find better relay settings which provide reliable protection in large scale systems.

2. Relay Protection Coordination Problem

In a protection scheme, each primary relay should operate as fast as possible to clear the fault in a system. If the operation time of a relay takes longer than an acceptable time, the damage on the faulty equipment would be severe with serious consequences. In other words, minimizing the total operation time of relays decreases the risk and stress on the protected equipment which can be depicted as an optimization objective function:

$$\text{OF=min } \sum_{i=1}^{n} t_i \tag{1}$$

where, t_i is the operation time of the relay R_i, and n is the number of relays. Based on the characteristic curves of relays, the objective function can be defined in (2):

$$t_i = \frac{\lambda \times TMS_i}{\left(\frac{I_{F,i}}{PS_i}\right)^{\eta} - 1} + \text{L} \tag{2}$$

where, depending on the type of relays, the characteristic constants λ, L and η are selected [16]. The component $I_{F,i}$ is the fault current passing through the current transformer and transformed by its secondary windings to be sensed by relay R_i. In (2), for a proper operation of an individual relay, each component includes a set of constraints:

$$t_{i,min} \leq t_i \leq t_{i,max} \tag{3}$$

where $t_{i,min}$ is the minimum operating time for relay R_i for a fault within its zone of protection and $t_{i,max}$ indicates maximum operating time of the relay.

With different TMS settings, a relay can respond to faults with different speeds and criterion which is proportional to the operating time. Also, the plug setting of the relay (PS) along with TMS, affect the time of operation where both include their constraint as follows:

$$TMS_{i,min} \leq TMS_i \leq TMS_{i,max} \tag{4}$$

$$PS_{i,min} \leq PS_i \leq PS_{i,max} \tag{5}$$

where $TMS_{i,min}$, $PS_{i,min}$, $TMS_{i,max}$, $PS_{i,max}$ are the minimum and maximum values of TMS and PS of relay R_i. To avoid mal-operation of a relay with normal load or slight overload current, the minimum pickup current setting is selected bigger than the maximum load current. The maximum plug setting is chosen not greater than the minimum fault current [17,18].

The above constraints can ensure the correct operation of an individual relay not a primary-backup pair. Therefore, to coordinate adjacent relays as primary and backup relays, the primary relay should operate as fast as possible within its acceptable boundaries. If it fails to act, its backup relay needs to take over the tripping action with a minimum time.

The minimum operating time of backup relay must be small but yet greater than the operating time of primary relay. Therefore a coordination time interval (CTI) is added to the constraints to satisfy the proper coordination scheme:

$$t_{b,j} - t_{m,i} \geq CTI \tag{6}$$

$$CTI = t_{CB} + t_{os} + t_{saf} \tag{7}$$

where, $t_{b,j}$ is the operating time of backup relay R_j and $t_{m,i}$ is the operating time of main relay R_i. In (7), the CTI depends on the circuit breaker opening time t_{CB}, relay over-travel time t_{os} and the safety factor time t_{saf} for CT saturation, setting errors, contact gaps, etc. Normally, t_{CB} is 0.08s (5 cycles), t_{os} is 0.10s and t_{saf} depend on the situation can be set around 0.1 to 0.22s (0.22s according to the IEEE standard [19]).

3. Fast Coordination Method

Meta-heuristic algorithms such as PSO, GA, DE, ACO and etc., are time consuming with higher chance of local value achievements which make them defective in real protection applications, therefore a simple and yet robust approach is introduced in this section which can be applied on almost any algorithm for relay coordination or similar tasks.

Optimization of the total operating time of relays in (1) requires the satisfaction of (2) to (6) while these constraints make the computation time of the algorithm quite long and tedious. As the systems are normally meshed, ring or two way power flow systems, directional relays are the proper choice for protection. Checking and finding proper TMS and PS settings for all relays which can satisfy all mentioned constraints, brings a burden to the optimization algorithms and this process consumes a long and impractical time. These issues push the applied algorithms to find local values rather than global values. A simple but very effective solution that is presented here can remarkably reduce the computation time to a very low value and push the algorithms to go toward the global value and achieve the optimum answer.

As the relays in a two way current flow system are directional, we can intuitively see two directions, left and right. However the relays can only see one direction, left or right. It divides all relays of the system into two groups, namely left side group and right side group. The relays in the left side group can only measure and react to the current flowing from left to right and the relays in the right side group can only measure the current flowing from right to left. As the operating time of relays need to be minimized, the conventional objective function in (1) can be redefined into sum of two objective functions with less unnecessary constraints:

$$\sum_{i=1}^{n} t_i = \sum_{l=1}^{k} t_l + \sum_{r=1}^{h} t_r \tag{8}$$

$$n = h + k \tag{9}$$

$$t_{l,min} \leq t_l \leq t_{l,max} \tag{10}$$

$$t_{r,min} \leq t_r \leq t_{r,max} \tag{11}$$

$$TMS_{l,min} \leq TMS_l \leq TMS_{l,max} \tag{12}$$

$$TMS_{r,min} \leq TMS_r \leq TMS_{r,max} \tag{13}$$

$$PS_{l,min} \leq PS_l \leq PS_{l,max} \tag{14}$$

$$PS_{r,min} \leq PS_r \leq PS_{r,max} \tag{15}$$

$$t_{b,l} - t_{m,l} \geq CTI \tag{16}$$

$$t_{b,r} - t_{m,r} \geq CTI \tag{17}$$

where, t_l and t_r are the operating time of left and right group relays respectively, k shows the number of left side relays and h shows the number of right side relays. Sum of left side relays indicate the operating time of all left side relays and sum of right side relays indicate the operating time of all the right side relays. The coordination constraints in (3) to (6) are divided into two groups of constraints which are shown in (10) to (17). The two objective functions in (8) must satisfy their own constraints namely with same subscripts. The relays in both right side and left side groups have the same manufactured TMS settings, therefore:

$$TMS_{l,min} = TMS_{r,min} = TMS_{i,min} \tag{18}$$

$$TMS_{l,max} = TMS_{r,max} = TMS_{i,max} \tag{19}$$

that shows an equivalent form of (4) in (12) and (13). It implies that the total number of relays which used to be optimized based on OF (1) and constraints (3) to (6), are now divided into two groups and optimized separately. Their new optimization procedures will check their independent constraints among (10) to (17) and each constraint involves few relays not all the relays. This process mitigates the complexity of a problem into a simpler form.

As the relays need to be coordinated with their adjacent proper relays as primary and backup relays, for an assumed relay, its backup relay will be the one which is nearest but in back side of it opposite to the direction of flowing fault current. The nominated backup relay will be definitely a same direction directional relay in the same group. In other words, if a left side relay is selected as primary relay, the backup relay will be a left side relay and vice versa. This fact agrees with both theory and practice and also proves our mathematical approach for coordination problems and are shown in (16) and (17). Two case study systems are investigated with the proposed solution.

Fig. 1 shows a ring system with 12 directional over-current relays as protection scheme. The left side relays can only observe the flow from left to right therefore the relays with odd numbers in this figure belong to the left side relay group. The right side relays which are capable of observing the current flowing from right to left, are marked with even

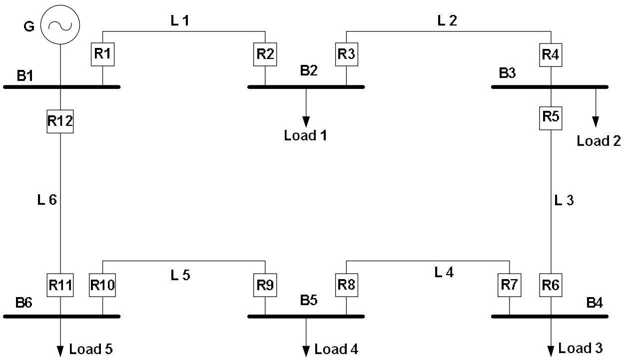

Fig. 1. A 6-bus ring system as case study 1

numbers in this figure. Relays R_1, R_3, R_5, R_7, R_9, R_{11} belong to the left side group and relays R_2, R_4, R_6, R_8, R_{10}, R_{12} are right side relays.

Table A.1 in appendix shows the combination of primary-backup pair relays in this ring system that also verifies the accuracy of equivalent left and right side group classification. A 150 MVA, 33 kV source is connected to bus 1. Five loads are connected to B2-B6. In some more complex and larger rings, there may be some relays that have more than one backup relay to isolate the faulty portion. In such system, one of the backup relays might be found in another group however, it does not considerably affect the fast coordination process. This fact is considered in second case study system.

To optimize the operating time of all relays, now two separate and independent objective functions can be optimized then eventually, the sum of these two objective functions result in the total objective function of the relays. Through this innovative mathematical and practical method, the constraints of all relays which used to be checked at the same time, are divided into two sub-optimization criteria. As it can be seen, the optimization procedure of left side group is totally independent of optimization procedure of the right side group.

Therefore, a coordination algorithm just needs to satisfy the constraints of one independent group at one time not all relays unnecessarily. This approach can remove the unnecessary computational time of other irrelevant relays hence increasing the calculation speed of algorithms dramatically. This manipulation helps the evolutionary algorithms to find more feasible values that satisfy all the constraints. The optimum value as global value is selected among the feasible values. Therefore, both computation time and the values are optimized efficiently.

4. Analytical Results

The proposed method can be applied on any optimization algorithm for coordination problem. Here, a PSO algorithm is designed and the directional overcurrent coordination problem is studied both with and without this method to investigate the performance of this new approach.

Two scenarios are considered, one a PSO algorithm without using our method, another with the help of the proposed method. In first case, the OF is assigned in (1), and for the second case, proposed equivalent form (8) is considered as the OF.

In PSO, the next movements of the particles are updated based on the best experience, global experience and the present experience of particles in the search space. The update process follows:

$$v_{nd}^{t+1}=w\times v_{nd}^{t}+c_1\times\text{rand}\times(Pbest_{nd}-x_{nd}^{t})+ c_2\times\text{rand}\times(Gbest-x_{nd}^{t}) \tag{20}$$

$$x_{nd}^{t+1}=x_{nd}^{t}+v_{nd}^{t+1} \tag{21}$$

$$w=w_{max}-\frac{w_{max}-w_{min}}{maxiter}\times iter \tag{22}$$

We assume that all the parameters in these two cases are same, therefore in Eq. (20-22), c_1 and c_2 are equal to 2, and w is a factor of w_{min} and w_{max} with values 0.4 and 0.9 respectively, x_{nd}^{t} and v_{nd}^{t} depict the present position and velocity of n^{th} particle in a D-dimensional search space. The case study in Fig. 1 includes 12 relays, and because each relay has two control settings (TMS and PS), therefore n is 24 and population size is chosen 60 (d=60). The maximum iteration is set to 100. In this analysis, all relays are assumed standard inverse definite minimum time (IDMT) type and the ratio of their current transformers are 500:1. Therefore, according to IEC and IEEE standards, the relay characteristic constants λ, L and η are 0.14, 0 and 0.02 respectively. The relays are digital relays and CTI is considered 0.2s. The minimum and maximum operating time of each relay is set to 0.1s and 4s. Here, as for microprocessor based relays, the continuous form of TMS and PS are considered as relay settings [5, 20-23, 30].

The case study system has been modeled and the load power flow and fault analysis of the system are all executed in DigSILENT Power Factory software version 15.1. Then, based on the collected data from this software, the protection coordination scheme has been designed and analyzed with MATLAB R2013a version 8. The analysis has been conducted on a computer with 3.3 GHz CPU.

Table 1 shows the maximum fault current passing through the primary winding of each CT while for each primary and backup relay coordination, near-end three phase to ground fault has occurred in their protection

Table 1. Maximum fault current

relays	$I_{f\,max}$(kA)	relays	$I_{f\,max}$(kA)
1	14.104	7	5.61
2	7.67	8	6.011
3	7.659	9	6.015
4	6.015	10	7.659
5	6.011	11	7.67
6	5.61	12	14.104

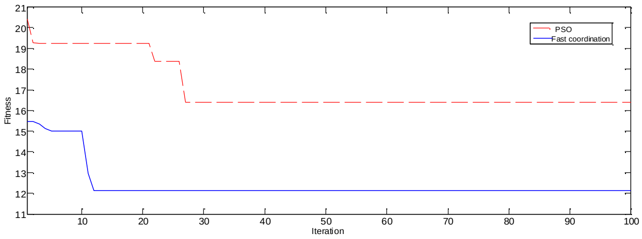

Fig. 2. Proposed fast and accurate relay coordination method compared with PSO

Table 2. Optimum coordinated values for DOCRs

Relay	PSO		Fast coordination	
	TMS	PS	TMS	PS
1	1.0959	2.3586	0.86964	1.9875
2	0.12295	0.90587	0.11123	1.7939
3	1.0533	2.2404	0.75902	1.5247
4	0.19443	1.5088	0.34013	0.95958
5	0.91226	2.3373	0.50658	1.1657
6	0.33148	0.96635	0.33447	1.9024
7	0.8479	1.8964	0.45816	0.80947
8	0.66102	1.5459	0.57752	0.89696
9	0.58091	2.2082	0.24481	2.0276
10	1.0351	0.66415	0.63038	1.2293
11	0.41675	2.2447	0.14374	0.74976
12	0.94357	1.7304	0.8789	0.77872
OF	**16.3829**		**12.1288**	
Time	**766.94**		**1.1322**	

zones. This process and the obtained data are executed in DigSILENT.

The 33 kV overhead lines in 6-bus ring case study system are stretched to 5km. The lines and load parameters of power flow analysis in DigSILENT software are shown in Table A.2 and A.3 in appendix, respectively.

The calculation results of the studied system in Fig. 2 show the optimization process of PSO algorithm with and without proposed fast coordination method. The final optimum values are shown in Table 2. It is deduced that, the proposed fast coordination method has a remarkable speed with an extremely low computation time compared with PSO algorithm. For a 12 relay system, the proposed method spent 1.1322s while PSO spent a much longer and improper time of 766.94s to run the calculations. After 12 iterations, the proposed method achieved the best optimal coordination values but for PSO, it achieved other non-global values after 27 iterations. In addition, the optimized result of the proposed method is much better than the PSO showing the great performance of this new approach. Also, this solution has a very low iteration which makes it a desirable tool for relay coordination problems.

The slow calculation procedure of such a normal evolutionary algorithm (without fast coordination method) cannot satisfy the continuous monitoring and protection of a large scale system or a flexible smart grid where loads and distributed generations [24-27] continuously connect or disconnect themselves to the grid and change the dynamic situation of the grid. The protection of a smart grid will be more intensive and extremely complicated in presence of fluctuations and a quite long time consuming algorithm without providing optimum results, is not able to follow the instantaneous state of the grid therefore the online/offline protection scheme based on such algorithms would result in mal-operation and serious damages. But, with the aid of the proposed fast coordination method that can be added as a patch to these algorithms, the time consumption will be dropped and it allows these sorts of algorithms to follow the current situation of a grid and provide a proper protection scheme online or offline with high reliability, fast calculation and optimum settings. One of the main obstacles of a future smart grid is integration of intermittent renewable energy sources into the system. This method with fast analysis procedure can provide a safe and smooth integration of renewable energy sources such as PV and wind farms [28-29] with higher reliability in relay coordination.

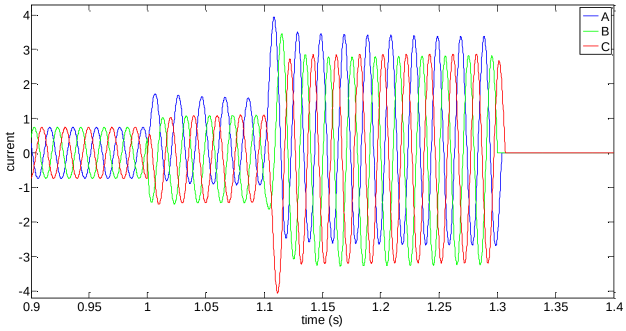

Fig. 3. Three phase current waveforms in presence of fault on the line 6 with successful operation of relay 11

The relay settings obtained by proposed fast coordination method has much less computation burden and better fitness values. Dynamic performance of these relay settings under grid fault conditions have been also studied. The results confirm successful operation of the relays under fault conditions in the grid. To avoid repetition of similar performances, some of the figures are presented here. A three phase fault occurs on line 6 at t=1s. Based on the obtained relay settings with proposed method, relays 11 and 12 have successfully reacted to clear the fault and isolate the faulty line. Relay 12 tripped after 100ms and opened its associated circuit breaker. Relay 11 reacted after 300ms and opened its associated circuit breaker. Figs. 3, 4 show the three phase current and voltage waveforms under fault condition with successful operation of relay 11, respectively. Figs. 5, 6 show the three phase current and voltage waveforms under fault condition with successful operation of relay 12, respectively. Proper operation of these relays, successfully disconnected the faulty line from the healthy part of the grid.

The proposed fast coordination algorithm is also tested on a more complicated interconnected system with 24 relays. The nine bus case study system is taken from [30]

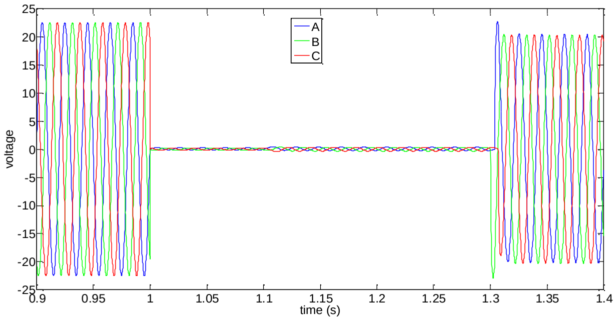

Fig. 4. Three phase voltage waveforms in presence of fault on the line 6 with successful operation of relay 11

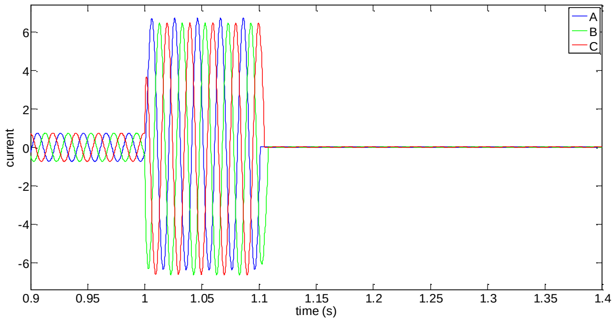

Fig. 5. Three phase current waveforms in presence of fault on the line 6 with successful operation of relay 12

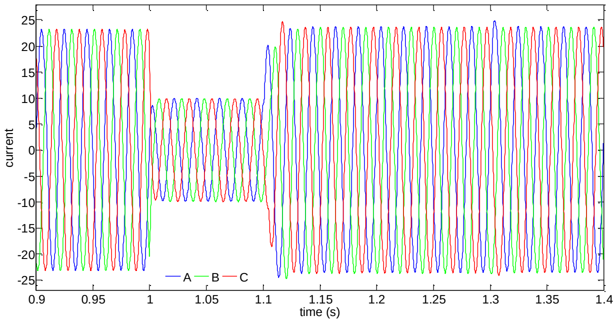

Fig. 6. Three phase voltage waveforms in presence of fault on the line 6 with successful operation of relay 12

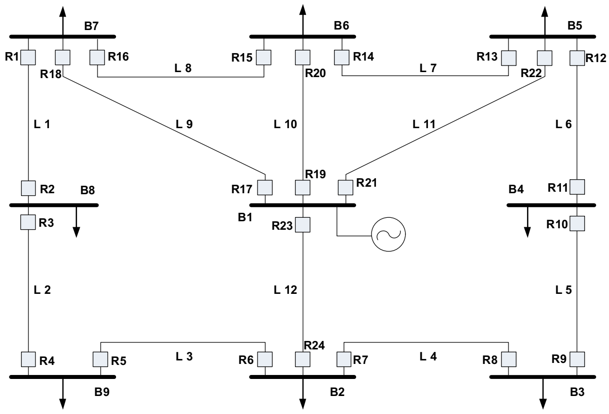

Fig. 7. Nine bus interconnected system with 24 DOCRs

and is shown in Fig. 7. The results are compared with the PSO and Genetic algorithm. The overcurrent relays are IDMT type w ith CT ratio of 500:1. Each relay has two setting values to be calculated (TMS and PS) thus, 48 dimensional variables exist to be optimized.

As shown in Fig. 7, a 100 MVA source is connected to the 33 kV distribution system at bus 1. The maximum fault current of the overcurrent relays are shown in Table 3 while the primary-backup pair relationship of the relays are presented in Table A.4 in appendix. For instance, if a fault occurs on line 3, both relays R_5 and R_6 must operate to isolate the faulty line. If relay R_6 cannot operate or clear the fault, its adjacent backup relay R_{23} and R_8 need to react and complete the protection task after a defined coordination time interval which is set 0.2 s here.

The proposed method is tested on this system and the results are represented together with PSO and also GA [30] in Table 4. The obtained relay setting values based on PSO and GA are 32.6058s and 32.683s respectively. However, if we reform the fitness function to an equivalent multi objective function, the objective function is calculated with more feasible solutions and much better values as optimum results. The fast coordination process has achieved best TMS and PS relay setting with final operating time of t=16.877 s. The result of fast coordination method shows a great efficiency in protection operation and reducing energy dissipation. Therefore, application of this method on evolutionary algorithms can aid to mitigate the complexity of optimization problems into a simpler form. More feasible answers can be acquired if the proposed solution is used. Among those feasible answers, the global value is selected as optimum answer.

The illustrated data in Table 4 shows the optimum relay settings related to case study two. The first column shows the number of relays in the system shown in Fig. 7. The second and third columns show the optimum TMS and PS settings of the relays obtained by the proposed fast coordination method. The fourth and fifth columns are the relay settings obtained by PSO. The sixth and seventh columns are the relay settings obtained by GA. There are 24 relays in case study two, which need to be coordinated properly. The TMS and PS values obtained by the proposed method have provided the proper protection scheme. All the relays have been optimally coordinated and the total operation time of these 24 relays is 16.877 s. It means that sum of the operation time all relays for a fault in their protection zone is equal to 16.877 s, better than PSO and GA. TMS shows the delay time of the relay against a fault in the zone. PS setting shows the sensitivity of the relay against fault currents. Each relay has an operation time as the objective function shown in equations (2) and (8). The operation time of each relay is proportional to the TMS value, while it is nonlinear against PS value. Therefore,

Table 3. Maximum fault currents of 9-bus interconnected system

relays	$I_{f\,max}$(kA)	relays	$I_{f\,max}$(kA)
1	4.8636	13	3.6845
2	1.6344	14	4.1725
3	2.8114	15	4.1725
4	2.6105	16	3.6845
5	1.778	17	7.6112
6	4.3785	18	2.2717
7	4.3785	19	7.4358
8	1.778	20	2.6242
9	2.6105	21	7.6112
10	2.8114	22	2.2717
11	1.6344	23	7.9147
12	2. 8114	24	1.6655

Table 4. Optimum results with fast coordination compared with PSO and GA

R	**Fast Coordinate**		**PSO**		**GA**	
	TMS	PS	TMS	PS	TMS	PS
1	0.68525	0.69338	0.23957	1.9417	04766	1.4304
2	0.2001	1.1661	0.16755	1.4914	0.0711	1.3060
3	0.24803	2.211	0.16355	1.6397	0.3522	0.8872
4	0.17614	1.5304	0.212	1.3838	0.3245	0.5179
5	0.48611	1.2114	0.21158	1.0024	0.2738	0.5579
6	0.2414	1.4538	0.25986	1.5386	0.3982	0.7942
7	0.27313	1.3755	0.18505	0.53342	0.6148	0.2566
8	0.51434	0.67034	0.40071	1.0357	0.6793	0.2792
9	0.18482	1.7901	0.045781	1.9364	0.3337	0.7516
10	0.31993	1.4025	0.69891	0.93805	0.7991	0.3578
11	0.25253	0.96178	0.10955	0.71895	0.2139	0.7855
12	0.60888	1.4445	1.0927	0.51621	0.7484	1.3179
13	0.41701	1.0409	0.55174	0.95757	0.6977	0.4762
14	0.43797	2.4958	1.0104	0.91252	0.7254	0.7903
15	0.25818	1.0582	0.27163	2.2595	0.6425	0.3914
16	0.092243	2.2726	0.087386	1.9641	0.3107	0.6788
17	0.64311	1.3869	0.38819	1.327	0.7162	1.1122
18	0.041714	1.3691	0.063828	1.269	0.1264	0.4918
19	0.38426	1.6627	0.57134	2.0324	0.5226	1.4124
20	0.063179	0.53564	0.042707	1.8601	0.1217	1.9569
21	0.95542	1.4891	0.93442	2.17	0.7622	1.3553
22	0.07728	1.3737	0.062805	0.76427	0.0803	0.5859
23	0.38996	2.3968	1.0578	0.65678	0.8544	1.3365
24	0.283	0.81244	0.02769	1.7477	0.2508	0.2067
OF	**16.877**		**32.683**		**32.6058**	

nonlinear combination of both TMS and PS values should be considered in order to estimate the correct operation time of a relay. Also, different fault type and fault currents together with other factors, affect the operation time. For example, for the 21st relay in Table 4, the TMS setting value is 0.95542 with fast coordination method, while the TMS value with PSO is 0.93442. It may seem that the proposed method has bigger TMS setting value which may result in slower operation time of relay 21. However, each relay has two settings, TMS and PS. Considering both values of TMS and PS besides the fault current in the field, can determine the actual operation time of a relay. For the indicated relay 21, the PS value using the proposed method is less than PSO and nonlinear combination of these values result in better operation time and proper coordination scheme for the relays in the system. The data analysis has been performed in MATLAB and DigSILENT Power Factory software 100 times for each case study system. The results confirm the effectiveness of the proposed method in achieving proper relay settings in the grid.

5. Conclusion

Relay coordination problem is a complex issue especially in a large scale system. Although several meta-heuristic algorithms have been studied to address this problem but all of them involve large and impractical time consumption. Also, finding an optimum relay setting in such systems may not be reliable. In this paper, a simple method has been introduced that can be applied on optimization algorithms which as a result it bypasses their large time consumptions. Compared with PSO algorithm and GA as an example in this paper, the analytical results showed that the proposed method has a great performance with a remarkable speed and final optimum values for relay coordination. This fast coordination method can be applied in practice especially in a large scale systems and allows intelligent algorithms to be used in real relay coordination. It is also capable of handling smart grid protection with two way power flow systems.

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Appendix

Table A.1. Primary-backup relationship of the relays

fault zone	primary relay	backup relay	fault zone	primary relay	backup relay
L1	1	-	L4	7	5
	2	4		8	10
L2	3	1	L5	9	7
	4	6		10	12
L3	5	3	L6	11	9
	6	8		12	-

Table A.2. Line parameters in normal operation in case 1

Parameters	Values(per 5km)
Rated current	1.5 kA
Pos. Seq. Impedance, Z1	1.501874 Ohm
Pos. Seq. Impedance, Angle	87.1376 deg
Pos. Seq. Resistance, R1	0.075 Ohm
Pos. Seq. Reactance, X1	1.5 Ohm
Zero Seq. Resistance, R0	0. Ohm
Zero Seq. Reactance, X0	0. Ohm
Earth Fault Current, Ice	0. A
Earth Factor, Magnitude	0.3333333
Earth Factor, Angle	180 deg
Line length	5 km

Table A.3. Load parameters of 6-bus ring system in case 1

Load	P(MW)	Q(Mvar)
1	12	7
2	7	3
3	10	2
4	23	14
5	10	3

Table A.4. Primary-backup pair relays of 9-bus interconnected system in case two.

fault zone	primary relay	backup relay	fault zone	primary relay	backup relay
L1	1	17,15	L7	13	11,21
	2	4		14	16,19
L2	3	1	L8	15	13,19
	4	6		16	2,17
L3	5	3	L9	17	-
	6	8,23		18	2,15
L4	7	5,23	L10	19	-
	8	10		20	13,16
L5	9	7	L11	21	-
	10	12		22	11,14
L6	11	9	L12	23	-
	12	14,21		24	5,8

Mostafa Kheshti born in Iran in 1987, received the B.Sc. degree at Shiraz University of Technology, Iran and worked in Regional Dispatching Center of Fars Regional Electric Company. As a distinguished elite engineer and a member of the genius club in Iran, he was invited to join the school of electrical engineering at Xi'an Jiaotong University, China in 2011 where he got M.Sc. and PhD degrees (with honors) from Xi'an Jiaotong University, Xi'an, China in 2013 and 2017, respectively. He is a researcher in mathematical and physical properties of electric systems, smart grid and electricity dispatching field. His research interests include monitoring, control, protection and optimization of power grid with intelligent methods.

Xiaoning Kang born in Shaanxi, China, on March 2, 1968, received the PH.D degree from the Xi'an Jiaotong University, Xi'an, China, in 2006. Currently he works at Xi'an Jiaotong University as the dean of electric power department. His research interests include fault location, substation automation and transformer protective relaying.

Zaibin Jiao received his B.Sc. and MSc degree from Southwest Jiaotong University, Chengdu, China and the Ph.D. degree from the Xi'an Jiaotong University, Xi'an, China, in 2008. He joined Xi'an Jiaotong University in 2008, and currently works as a Lecturer. From 2011 to 2012, he visited the University of Hong Kong as a Post Doctoral Fellow. His areas of interest are power system protection and smart grid.