Optimization of Fuse-Recloser Coordination and Dispersed Generation Capacity in Distribution Systems

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Received: July 2013 Revised: December 2013 Accepted: March 2014

ABSTRACT
In this paper, a novel protection of coordinating optimization algorithm is proposed. Maximizing the penetration‘s dispersed generation and at the same time minimizing the fuse’s operating time are the targets.
A novel optimization technique, the Imperialistic Competition Algorithm (ICA), is applied to solve the problem. The results of simulations confirm that the proposed method leads to lower operating times of protective devices and higher possible DG penetration, compared with the traditional coordination techniques.

KEYWORDS: Fuse-recolser Coordination, Optimization, DG, Protection, ICA.

1. INTRODUCTION
Application of DG in distribution systems has increased in recent years. This is mainly due to the reliability and environmental considerations. A comprehensive survey of DG technologies, definitions and benefits has been presented in [1]. DG’s positive and negative impacts concerning the reliability of system’s power have been studied in [2-4].
High penetration of DG may result in the incoordination of overcurrent protective devices [5]. Therefore, the overcurrent problem of protecting coordination must be solved in the presence of DG. Several researches have been performed hereof:
In [5], first the fuse-recloser coordination problem has been solved. Then, the maximum possible value of DG short circuit capacity has been calculated, in order that the protecting coordinating is still valid. In [6], two cases have been studied. The first one is to determine the best DG location, to minimize. The number of fuses and reclosers incoordination for different fault locations. The second one is to change the TD of recloser to minimize the number of fuse and recloser incoordination for different fault locations. A simple adaptive overcurrent protection of distribution systems in the presence of DG has been presented in [7]. In this method, the course characteristics of the relays are updated by detecting the operating mode (grid connected or island) and the faulted section. Protective devices coordination with the presence of DG has been discussed and the fuse-fuse, fuse-recloser and relay-relay coordination have been studied regarding the Dg’s size and location. [8]. A microprocessor-based recloser has been presented in [9], to coordinate fuse-recloser in an actual distribution system with distributed generation. In [10], when a fault occurs then all the DGs will be disconnected promptly before any operating activity of protective devices.. This way, the conventional protecting coordinating is applicable. The impact of DG on the reliability of distribution systems considering protecting coordinating has been analyzed in [11]. In [12], first the effect of high DG penetration on protective devices has been studied. Then, a scheme has been proposed based on adaptive protection for different sizes, types and locations of DG to solve the problem. In [13], the optimal size of DG has been calculated using Optimal Power Flow (OPF), considering recloser fuse coordination. In [14], maximum capacity of DG at each node of the distribution system has been determined considering coordination protection. At the first stage, a single DG in the distribution system has been studied. At the second stage, two or more DGs in separate nodes have been considered. The superconducting fault current limiter (SFCL) has been used in [15], to restore the coordination of protective devices in the presence of wind-turbine generation. Coordination of the directional overcurrent relays has been studied with the DG presence in [16].
Regarding to this purpose, the impedance type of the Fault Current Limiter (FCL) is used.
The optimal size of wind-turbine generator, considering voltage regulation and overcurrent relay coordination, has been calculated in [17].

In this paper, optimization of the operation times of protective devices and DG short circuit capacity is performed. For this purpose, first an appropriate objective function is introduced. Then this function is minimized using Imperialistic Competition Algorithm (ICA). The Imperialistic Competition Algorithm (ICA) has been described, in detail in [18-24].

In section II, the coordination of fuse-recloser in the presence of DG is described. The Imperialistic Competition Algorithm and the proposed method have been introduced in sections III and IV. In section V, simulation results are presented and analyzed. Discussion, conclusion of the paper and references appear in sections VI, VII and IIX, respectively.

2. FUSE-RECLOSER COORDINATION IN THE ORESENCE OF DG

In this section, the effect of DG on the fuse-recloser coordination is analyzed. In the conventional distribution system when a fault occurs the following order of operation must be satisfied:

- First, fast operation mode of recloser operates to remove the fault.
- In the second step, the recloser restores the system.
- In the third step fuse operates, if the fault is permanent.
- Slow operation mode of recloser is the backup protection for steps 1 and 3.
- Relay is backup protection for the above mentioned protections.

Fig. 1 depicts the time-current characteristics of fuse and recloser. Curves 1 and 2 show the fast and slow modes of recloser, respectively. Curve 3 shows the fuse characteristic. Regarding to the figure1 characteristic is sharper than recloser, fuse-recloser coordination is valid if that fault current is greater than I_1 and smaller than I_2.

In Fig. 1. Only in this range, the previously mentioned order of operation is observed.

Fig. 2 shows a sample typical distribution system with DG [5]. For this system, fault currents seen by recloser and fuse are given in Table I. In this table, I_{fuse} and $I_{recloser}$ are the fault currents seen by the fuse and recloser, respectively. $I_{substation}$ and I_{DG} are the fault currents flowing from substation and DG, respectively [5].

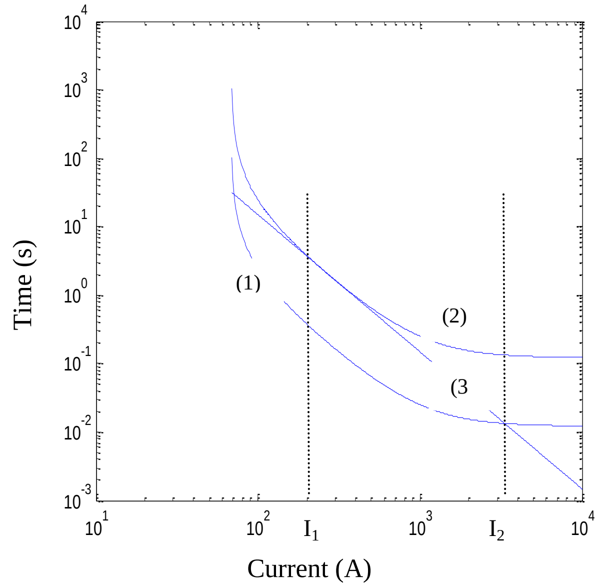

Fig. 1. Fuse and recloser time-current characteristics

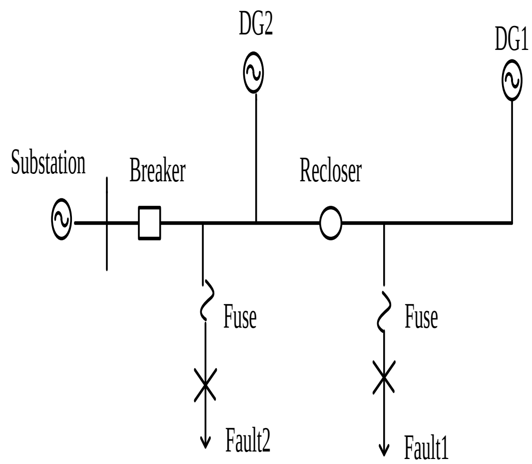

Fig. 2. Sample typical distribution system

Table 1. Description of fault currents seen by recloser and fuse

Case	DG source	Fault location	Description
1	DG 1	Fault 1	$I_{recloser}=I_{substation}$ and $I_{fuse}=I_{substation}+I_{DG}$
2	DG 1	Fault 2	$I_{recloser}=I_{DG}$ and $I_{fuse}=I_{substation}+I_{DG}$
3	DG 2	Fault 1	$I_{recloser}=I_{substation}+I_{DG}$ and $I_{fuse}=I_{substation}+I_{DG}$
4	DG 2	Fault 2	$I_{recloser}=0$ and $I_{fuse}=I_{substation}+I_{DG}$

In case 1 of Table 1, fault current seen by the fuse is greater than the fault current seen by the recloser. Therefore, incoordination of the fuse and recloser may occur, since the fuse may operate before the fast mode operation of recloser.

In case 2, following conditions are possible:

When observed fault current by the recloser is less than the original recloser setting the fuse will operate in this case. Therefore, fuse will operate in its first phase.

When observed fault current by the recloser is greater than the original recloser setting. In such cases, the fault current seen by the fuse is sum of the fault current flowing from DG and the fault current flowing from substation, while the fault current seen by the recloser is equal to the fault current flowing from DG. The fault current flowing from DG is much less than the fault current flowing from substation. Therefore, fuse operates in first stage.

In case 3, fault currents seen by both fuse and recloser are increased, due to the presence of DG. In this case, incoordination may occur when the fuse operates before the fast operation mode of recloser, due to the sharper time-current characteristic of the fuse. If the short circuit capacity of DG increases, the probability of incoordination will also be increased.

Fault current seen by the recloser in case 4 is zero and in this case, the fuse operates.

In this research, the purpose is to obtain a proper fuse curve to minimize the operation times of protective devices and, at the same time, to maximize the possible DG short circuit capacity. This way, the utilities will be able to increase the penetration of DG without violating the coordination of protective devices.

3. IMPERIALISTIC COMPETITION ALGORITHM

The Imperialistic Competition Algorithm (ICA) has been introduced in 2007, by Atashpaz-Gargari and Lucas [18]. In this optimization algorithm, the population called countries is in two types: colonies and imperialists. Each imperialist, together with some of colonies, form an empire. ICA is based on the imperialistic competition among these empires. The algorithm converges when there is just one empire, which is the best result. ICA validity has been proved by testing on different benchmark functions [18] and optimization problems, in power systems, such as DG placement [19-20], optimal PMU placement [21], capacitor placement [22] , optimal DG placement in distribution systems [23] and unit commitment [24].

The Imperialistic Competition Algorithm (ICA) may also be used to solve the optimization problem of optimum fuse-recloser coordination. The ICA have started the optimization with initial countries, similar to the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), which start with initial population. Fig. 3 shows the flowchart of ICA. After generating initial countries, which satisfy the optimization problem constraints in the first stage, some of the initial countries, which have more power (less cost), are selected as initial imperialists. Other countries, which have less power, are selected as the colonies of these selected imperialists. In the next stage, the colonies start the assimilation stage by moving toward their related imperialist, to achieve better position with less cost. After colonies movement toward imperialist, they may reach a position, which is better than the relevant imperialist position. In such a case, this colony becomes the new imperialist and the titles are exchanged. Afterward, the imperialistic competition begins among empires. The imperialistic competition will lead to the increase in the power of powerful empires and the decrease in the power of weaker ones. This way, the weaker empires lose their colonies and become weaker and, eventually, eliminated after losing all their related colonies. These competitions among the empires will cause the countries to converge to a position, in which there is only one Superpower Empire in the world and all the other countries are its colonies. This country is the global optimum which has the least cost.

In this algorithm, each country consists of optimization variables. Optimization variables determine the country location in the optimization space. The optimization space is where the optimization variables satisfy the coordination constraints. Power of each country, which is in reverse relationship with the amount of objective function, depends on the amounts of optimization variable. In this paper, these variables include the fuse parameters and the size of DG.

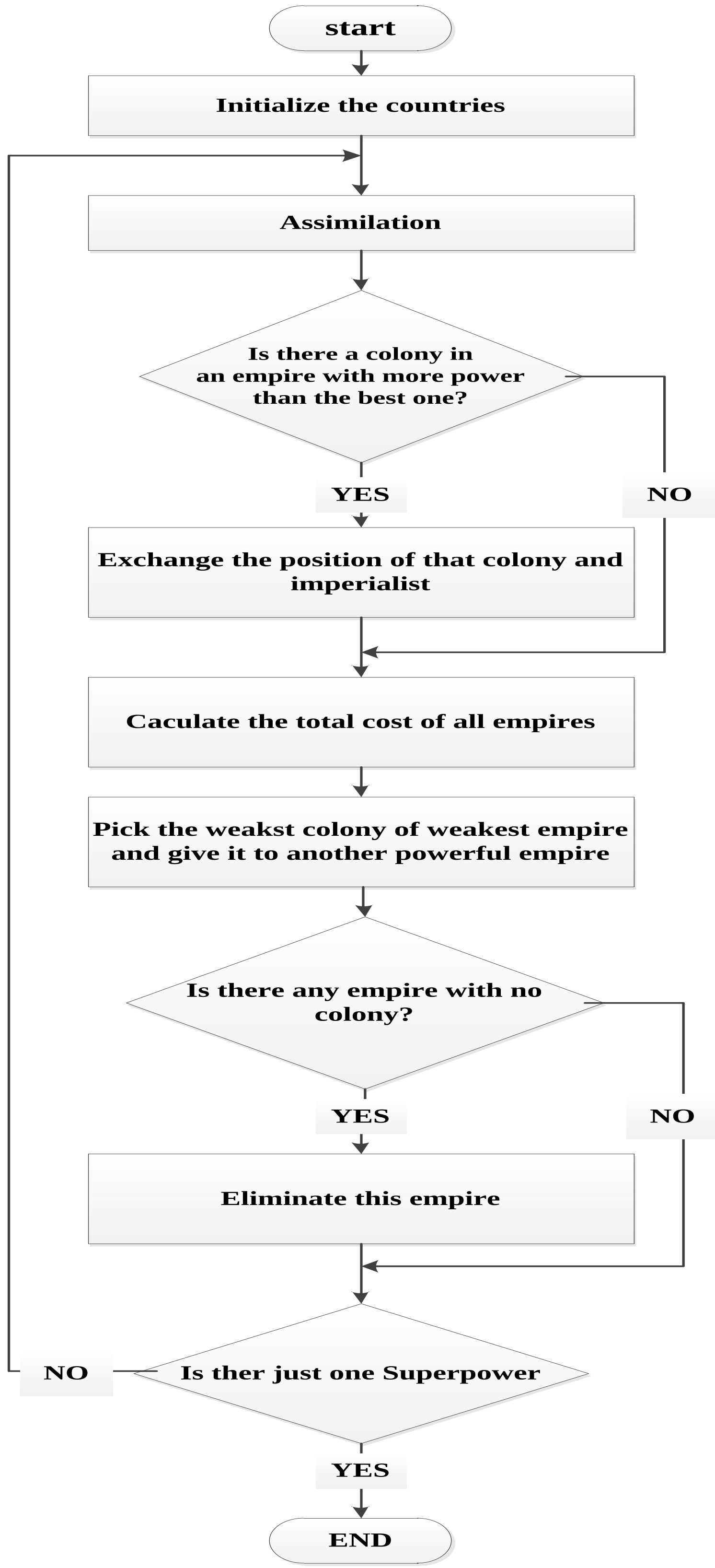

Fig.3. The ICA flowchart

4. THE PROPOSED COORDINATION METHOD

In order to describe the proposed algorithm, a typical radial distribution system is used, as depicted in Fig. 4 [25] . In this system, the time-current characteristics of overcurrent relay and recloser may be represented by equation (1):

$$t(I) = TD(\frac{A}{M^{p}-1} + B) \quad (1)$$

Where
t: operating time of device
I: fault current seen by the device
TD: Time Dial Setting
M: ratio of I/I_{pickup} (I_{pickup} is the relay current set point)
A, B, p: constants for the particular curve characteristics.

The time-current characteristics of fuses are represented by equation (2):

$$t(I) = 10^{b} I^{a} or \log(t) = a \times \log(I) + b \quad (2)$$

Where t and I are operation time and fault current, respectively. The characteristics of fuses are determined by the parameters a and b. These parameters are calculated by the proposed optimization technique, in order that minimum operating times are obtained for the fuses, while at the same time the short circuit capacity of DG is maximized.

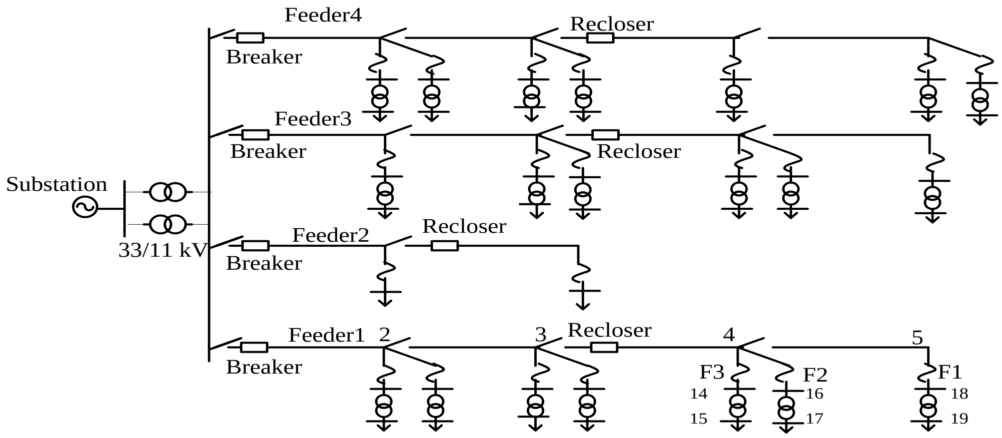

Fig. 4. A typical distribution system

Fig.5 illustrates the main stages of proposed coordination method. At the first stage, the fastest characteristic is selected for the fast operation mode of recloser. At the second stage, an optimization problem is solved to obtain the best characteristics for the fuses. Finally, at the third stage, the slow mode operation of recloser is selected in coordination with the fuse characteristics.

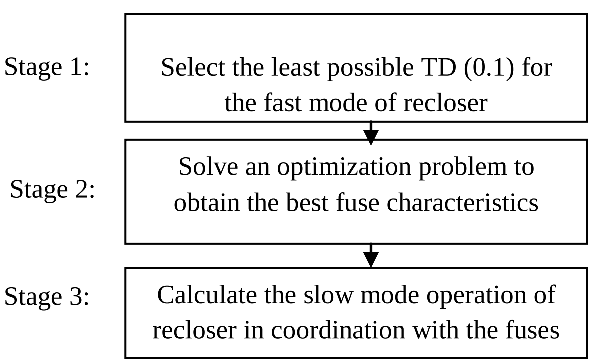

Fig. 5. Main stages of the proposed coordination Method

The optimization problem of stage 2 is described as follow:

Considering feeder 1 of Fig. 3, the objective function is the sum of fuse operation times for fualts occuring on buses 14 to 19:

$$F = t_{f1} + t_{f2} + t_{f3} + t_{f4} + t_{f5} + t_{f6} \quad (3)$$

$$F = (10^{b_1} I_1^{a_1}) + (10^{b_2} I_2^{a_2}) + (10^{b_3} I_3^{a_3}) + (10^{b_1} I_4^{a_1}) + (10^{b_2} I_5^{a_2}) + (10^{b_3} I_6^{a_3}) \quad (4)$$

In above equation, *a1* and *b1* are the parameters of the *F1* fuse. *a2* and *b2* are the parameters of the *F2* fuse. *a3* and *b3* are the parameters of *F3* fuse.
I_1 : fault current of *F1* fuse, for fault occuring on bus 19 in the presence of DG.
I_2 : fault current of *F2* fuse, for fault occuring on bus 17 in the presence of DG.
I_3 : fault current of *F3* fuse, for fault occuring on bus 15 in the presence of DG.
I_4 : fault current of *F1* fuse, for fault occuring on bus 18 in the presence of DG.
I_5 : fault current of *F2* fuse, for fault occuring on bus 16 in the presence of DG.

I_6 : fault current of *F3* fuse, for fault occuring on bus 14 in the presence of DG.
Therefore the optimization problem is formulated as follow:

$$\begin{aligned} & Min(F) \\ & Subject\ to: t_{f_i}(I_j) > t_{recloser(fast\ \ mode)}(I_j) \\ & for\ j = 1,2,...,6\ \ and\ \ i = 1,2,3 \\ & -4 < a_i < 0 \\ & 3 < b_i < 7 \\ & 0 < I_{DG} < 5000 \end{aligned} \tag{5}$$

5. SIMULATION RESULTS AND ANALUSIS

The typical distribution system, depicted in Fig. 4, is simulated using the Electro-magnetic Transients Program (ATP/EMTP). Table 2 shows nominal and pickup currents of overcurrent relay and recloser.

Table 2. Nominal and pickup current of recloser and relay

	Current(A)
$I_{nom,\ relay}$	50.5
$I_{nom,recloser}$	37.0027
$I_{pickup,relay}$	75.75
$I_{pickup,recloser}$	55.5

TD of the recloser in fast operation mode is assumed to be 0.1. Other parameters of the recloser are *A*=28.2, *B*=0.1217, *p*=2 [5]. In this section, cases 1 and 3 of table I are investigated, since only in these cases incoordination is probable.

A. DG Location on bus 5 (case 1 of table I)

In case 1 of table I, fault current seen by the fuse is greater than the fault current seen by the recloser. Therefore, incoordination of the fuse and recloser may occur, since the fuse may operate before the fast mode operation of recloser. The results of the ICA optimization technique are listed in Table 3.

Table 3. Value of DG short circuit current and parameters of fuse curves

$I_{DG}(A)$	Fuse 1		Fuse 2		Fuse 3	
	a_1	b_1	a_2	b_2	a_3	b_3
332.83	-2.45	6.14	-2.76	6.99	-2.21	5.48

Figs. 6, 7 and 8 compare the fuse characteristics of this work with those of [5]. Considering these figures, since the fault current is greater than 100A, the fuses are faster than those of [5]. Load current is 37A and protection devices are restraint for this current. Moreover, maximum DG short circuit capacity is 5.5486MW, which is greater than the 2.0026(MW) of [5]. Considering Table I, the fuses see the fault current flowing from DG and substation. On the other hand, operation time of fuse has inverse relation with fault current (see equation 2, in which *a* is negative). Therefore, minimization of fuse operation times will simultaneously result in the maximization of DG short circuit capacity.

Once the optimization problem of equation (5) is solved, the fuse characteristics are obtained. Now, the slow mode operation characteristic of recloser is calculated in coordination with the obtained fuse characteristics. The minimum fault current has been used to coordinate *F1*, *F2* and *F3* fuses with the slow mode operation of recloser (the fuses must operate before the slow mode operation of recloser operates). In this way, *TD* of slow mode operation of recloser has been calculated. Table 4 shows *TD* of slow mode operation of recloser to coordinate with *F1*, *F2* and *F3*. Fig. 9 shows the coordination of fuse and recloser for faults occurring on buses 18,19.

Relay is coordinated with fuse and recloser after solving optimization algorithm, based on coordination of overcurrent relays method. The upstream relay is coordinated with downstream protection devices. In such case, the relay should be coordinated with the downstream protection which has the maximum operation time.

Table 4. *TD* of slow mode operation of the recloser

fuse	*TD*	Final value of *TD*
1	1.44	2.4
2	1.76	
3	2.4	

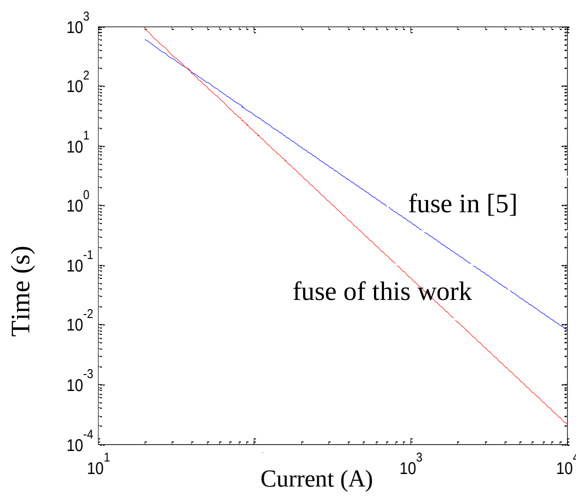

Fig. 6. Fuse characteristics for *F1*

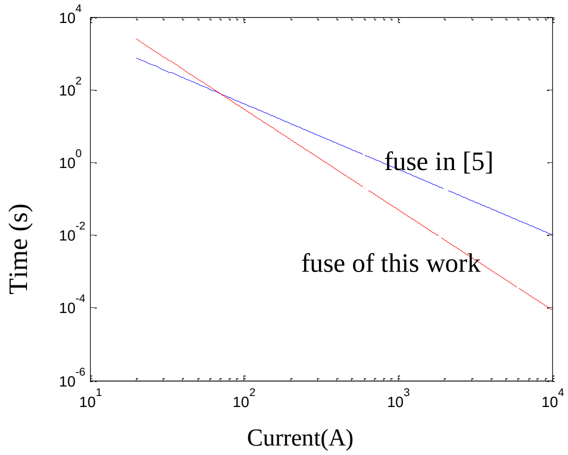

Fig. 7. Fuse characteristics for *F2*

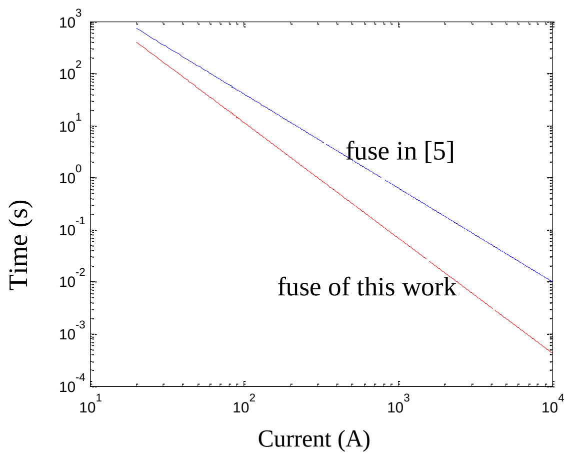

Fig. 8. Fuse characteristics for *F3*

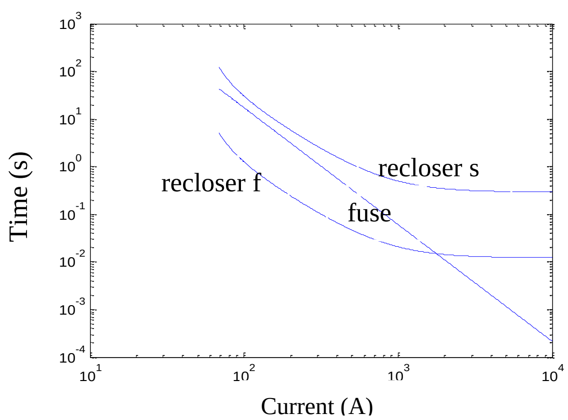

Fig. 9. *F1* fuse and recloser curves

B. DG Location on bus 3 (case 3 of table I)

In case 3 of Table 1, fault currents seen by both fuse and recloser are increased, due to the presence of DG. In this case, incoordination may occur when the fuse operates before the fast operation mode of recloser, due to the sharper time-current characteristic of the fuse. If the short circuit capacity of DG increases, the probability of incoordination will also increase.

The results of ICA optimization technique are listed in Table 5.

Table 5. value of DG short circuit current and parameters of fuse curves

$I_{DG}(A)$	Fuse 1		Fuse 2		Fuse 3	
	a_1	b_1	a_2	b_2	a_3	b_3
1820.61	-2.52	6.89	-2.23	5.94	-2.23	5.96

Figs. 10, 11 and 12 compare the fuse characteristics of this work with those of [5]. These figures show that the fuse curves are sharper and faster than those of [5]. Load current is 37A and protection devices are restraint for this current. Moreover, maximum DG short circuit capacity is 30.3514MW which is much greater than the 2.73 MW DG capacities of [5].

TD of the slow operation mode of recloser in this case has been shown in Table 6. Also, the coordination of fuse and recloser for faults on buses 18,19 has been shown in Fig 13.

Table 6. *TD* of slow mode operation of the recloser

fuse	*TD*	Final value of *TD*
1	4.98	4.98
2	2.72	
3	2.77	

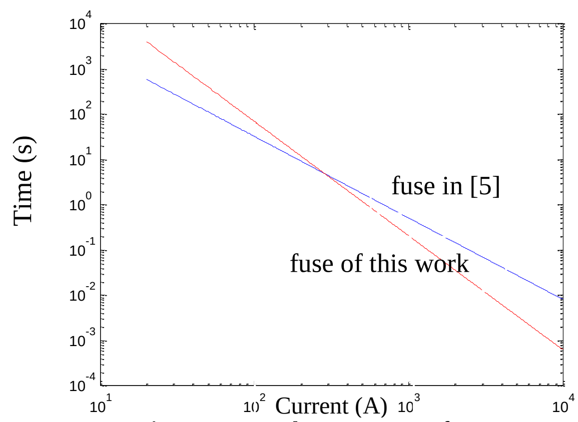

Fig. 10. Fuse characteristics for *F1*

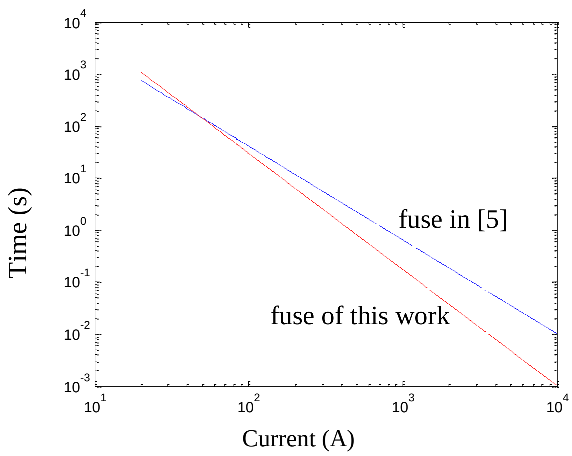

Fig. 11. Fuse characteristics for *F2*

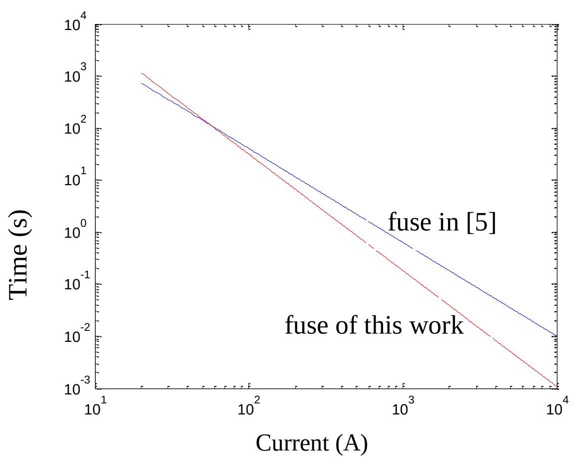

Fig. 12. Fuse characteristics for *F3*

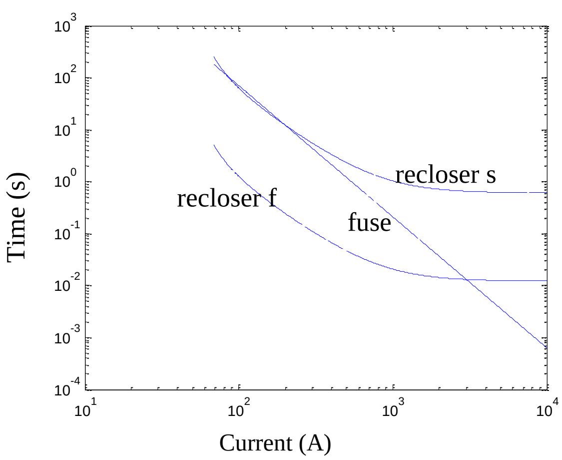

Fig. 13. *F1* fuse and recloser curves

Fig. 14 shows coordination margin between fuse and recloser which is presented in [5] in comparing with case 3. Dashed curves are related to the presented fuse and recloser characteristic curves in [5] and the other curves are related to the fuse and recloser characteristic of this paper. Referring to Fig. 14, the coordination margin in this paper is greater than coordination margin presented in [5].

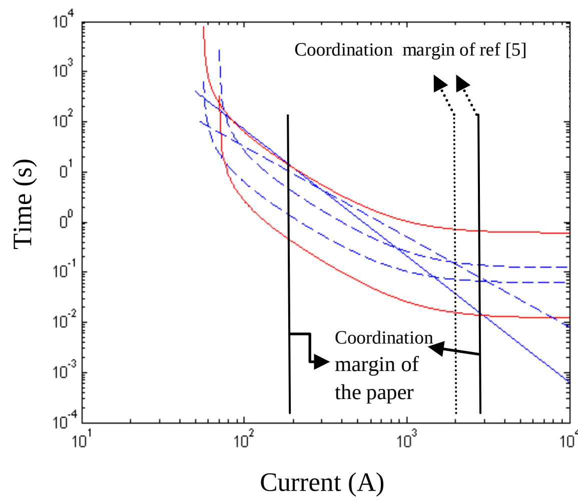

Fig. 14. Coordination margin presented in [5] in comparison with proposed algorithm

6. DISCUSSION

This work presents fuse-recloser coordination with DG's presence. The most significant advantages of this work comparing with the conventional coordination methods are summarized as follow::

- In the conventional protecting coordinating methods, presence of DG may easily violate the coordination. However, the results of proposed method of this work demonstrate that, if this new method is applied, it is possible to maintain the protecting coordinating even in the presence of DGs as much as 30 MW. Although this amount of DG capacity is not expected, these results show the robustness of the proposed method.
- The method is applicable to any distribution system, either with or without DG.
- DG short circuit capacity has been increased and at the same time, operation times of protective devices have been decreased in comparison with the previous methods, considering coordination of fuse-recloser.
- Coordination time between fuse and recloser operation is greater than zero in this method while, other methods have supposed zero coordination time between fuse and recloser.

- This method is applicable in two different conditions: first, fuse and recloser see the same fault current. Second, they see different fault currents.
- The fuse characteristic used in this paper is a standard characteristic [5].

7. CONCLUSION

High DG penetration in distribution systems may result in the incoordination of fuse-recloser. This incoordination has been demonstrated in this paper. Then, an appropriate objective function of operation times of fuses with unknown parameters has been proposed to maximize DG penetration and at the same time, minimize operation time of protective devices, considering coordination of fuse-recloser. As a result, parameters of fuses have been calculated. The Imperialistic Competition Algorithm is applied to solve the optimization problem. The results of simulations confirm that the proposed method obtains smaller protection times and greater DG short circuit capacity, compared with the conventional coordination methods.

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