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Imperialist Competition Algorithm for Distributed Generation Connections

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Abstract

This paper proposes an Imperialist Competition Algorithm (ICA) to maximize the benefits of distribution network operators (DNOs) accrued due to presence of distributed generation (DG) units in distribution networks. The sum of active loss reduction and network investment deferral incentives has been considered as objective function to be maximized in this study. The optimal location and size of DG units in the network are found considering various techno-economical issues. The application of the proposed methodology in the UK under current Ofgem financial incentives for DNOs is investigated. The strength of the proposed approach is validated by comparing the obtained results with other methods of the literature.

Index Terms

Distributed generation, Imperialist Competition Algorithm, active loss reduction, investment deferral.

I. Introduction

A. Motivation

The role of Distributed Generation (DG) units has become much more important with the deregulation of power industry. These units have been become an interesting option for Distribution Network Operators

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(DNOs) to meet the requirements of their customers. The main point of deregulation is to split generation, transport and consumption of electrical energy between independent parties. Therefore, DG units installed nowadays are not owned by Distribution Network Operators (DNOs). DNOs typically only give permission for connection of DG units to distribution network (i.e. check whether DG unit satisfies technical requirements). Although in unbundled environment the DNO does not decide about the location and size of DG units but these quantities have direct impact on DNO's benefits. The DG planning problem (finding the optimal size and location) is a Mixed Integer Non-Linear Problem (MINLP). Generally finding the global optimal solution of a MINLP problem is a difficult task. Therefore the DNO needs a computation tool to deal with this problem. This paper presents a new methodology to answer this need.

B. Literature review

The DG units charge the flow of energy over the feeders of the distribution network by injecting active and reactive power to their interconnection node. The DG units may bring different benefits for Distribution Network Operators (DNOs) such as: shorter construction period [1], network investment deferral [2], active loss reduction [3]–[5], environmental emission reduction [6] and reliability improvement [7], [8]. The benefits of DG units highly depend on the size and location of them in the network. Many methods have been proposed in the literature to find the optimal location and size of DG units in the network which have considered various technical aspects such as: voltage limits, feeder capacity limits and penetration level. Additionally, there are some regulatory issues which may change the potential benefits of DG units for DNOs. These frameworks are widely classified into two categories: DG owned and unbundled DNO [9]. In DG-owned DNO category, the DNO is allowed to perform DG investment. This gives DNO the opportunity to make decision about the size and location of DG units. The second category prohibits the DNO of DG ownership/investment. The DG units are installed and operated by DG owners. The main goal of DG operator/owners is maximizing its benefits. This can be used by DNO to identify the optimal location ans size of DG units as a guide for DG investors and steer their decisions. The DG-owned category has been highly investigated in the literature like [2], [10], [11]. Few literature deal with unbundled DNO like [12]–[14]. In [12], a Kalman Filter algorithm is proposed to find the optimal size of DG units to reduce active losses. In [13], a hybrid GA-OPF is proposed to find the size and location of a predefined number of DG units to increase the incentives received by DNO due to network reinforcement deferral and loss reduction. The Genetic Algorithm (GA) finds the connections nodes and the OPF finds the optimal size of DG units. In [14], an ordinal optimization approach for reducing the search space of the proposed problem in [13] which shows improvement in the results.

C. Contribution

A heuristic method named Imperialist Competition Algorithm (ICA) is proposed to find the optimal size and location of DG units to maximize the benefits of DNO. The proposed algorithm is robust and computationally efficient in comparison with previously proposed methods of the literature.

D. Paper organization

This paper is set out as follows: Section II presents problem formulation, Section III sets out the proposed solution method for solving the problem. The application of the proposed model and the simulation results are presented in Section IV and finally, the The conclusion is drawn in Section V .

II. Problem formulation

The DG sizing and placement is done for a predefined number of DG units, i.e. N_{dg}. The decision variables are the binary decision variable, i.e. ξ_i^{dg}, which shows the installation of a DG unit in bus i and also the capacity of installed DG, i.e. S_i^{dg}, in bus i. The constraints and the objective function are explained next.

A. Constraints

1) Power Flow Constraints: The power flow equations that should be satisfied for each sizing and placement scheme are as follows:

$$\begin{aligned}
P_i^{net} &= -P_i^D + \sum_{dg} P_i^{dg} \\
Q_i^{net} &= -Q_i^D + \sum_{dg} Q_i^{dg} \\
P_i^{net} &= V_i \sum_{j=1}^{N_b} Y_{ij} V_j cos(\delta_i - \delta_j - \theta_{ij}) \\
Q_i^{net} &= V_i \sum_{j=1}^{N_b} Y_{ij} V_j sin(\delta_i - \delta_j - \theta_{ij})
\end{aligned} \tag{1}$$

2) Operating limits of DG units : The DG units should be operated considering the limits of their primary resources, i.e.:

$$P_i^{dg} \leq \overline{P}_{lim}^{dg} \tag{2}$$

The power factor of DG unit is kept constant, as follows:

$$cos\varphi^{dg} = \frac{P_i^{dg}}{\sqrt{(P_i^{dg})^2 + (Q_i^{dg})^2}} = const. \tag{3}$$

3) Voltage profile: The voltage magnitude of each bus should be kept between the operation limits, as follows:

$$V_{min} \leq V_i \leq V_{max} \tag{4}$$

4) Capacity limit of feeders: To maintain the security of the feeders, the flow of current passing through them should be kept below their capacity limit, as follows:

$$I_\ell \leq \overline{I}_\ell \tag{5}$$

Where, I_ℓ is the current passing through feeder ℓ and $\overline{I}_\ell$ is the capacity limit of feeder ℓ.

5) Number of installed DG units: It is tried to find the optimal size and location of a predefined number of DG units in a given network. The total number of all installed DG units should be equal to a given number, i.e. N_{dg}, as follows:

$$\sum_{i=1}^{N_b} \xi_i^{dg} = N_{dg} \tag{6}$$

B. Objective Function

The proposed model maximizes the total benefits of DNO which is the sum of two incentives, namely, total incentive of network reinforcement deferral and total loss reduction incentive, as follows:

$$max\,\{OF\}$$

subject to:

$$(1) \rightarrow (6)$$

The values of incentives due to network reinforcement deferral and total loss reduction are formulated next.

1) Total incentive for active loss reduction: Different schemes exist for considering the effect of loss reduction on the benefits of DNO. One of the appropriate models reported in the literature is calculating the difference between total loss of the system before and after DG placement [9], [11], [13], [15]. In some models [11], the DNO should pay/receive equal to the electricity price multiplied by amount of loss reduction/increase and in some models [9], [13], [15] a fix incentive, i.e. ψ, is paid to DNO for each MWh reduction of active losses . This paper uses the second model as follows:

$$\mu_l = \psi \times (Loss^{nodg} - \sum_{i=1}^{N_b} P_{i,t}^{net}) \tag{7}$$

Where, $Loss^{nodg}$ is the active loss when no DG unit is installed in the network.

2) Total incentive for network reinforcement deferral: The network investment deferral effect of DG units is one of the important technical and economical values of DG units for DNO. This effect is even known as “non-wire solution” [16], to meet the load growth. One method for exact calculation of this deferral is integrated planning models [17] in which network reinforcement and DG planning are performed simultaneously. The other methods use simplifying assumptions by assuming that each MVA of installed DG reduces the need for reinforcing substation and feeders [13], [15]. In this model, the incentive due to investment deferral in network is proportional to the total installed DG in the network, as follows:

$$\mu_n = \gamma \times \sum_{i=1}^{N_b} P_i^{dg} \tag{8}$$

Where, γ is the coefficient of incentive for each MW of installed DG units.

The objective function is calculated as follows:

$$OF = \mu_l + \mu_n \tag{9}$$

The DG placement problem defined here is a mixed integer non-linear problem. Heuristic search methods have been successful in solving such problems. An ICA is proposed for solving the defined problem, in next section.

III. The proposed Imperialist Competition Algorithm

The Imperialist Competition Algorithm (ICA) was first proposed in [18]. It is inspired by the imperialistic competition. It starts with an initial population called colonies. The colonies are then categorized into two groups namely, imperialists (best solutions) and colonies (rest of the solutions). The imperialists try to absorb more colonies to their empire. The colonies will change according to the policies of imperialists. The colonies may take the place of their imperialist if they become stronger than it (propose a better solution). This algorithm has been successfully applied to PSS design [19] and data clustering [20]. The flowchart of proposed algorithm is depicted in Fig.1. The steps of the proposed Imperialist Competition Algorithm (ICA) are described as follows:

Step 1. Generate an initial set of colonies with a size of N_c.

Step 2. Set Iteration=1.

Step 3. Calculate the objective function for each colony using (9) and set the power of each colony as follows:

$$CP_c = OF \tag{10}$$

This means the less OF is, the more stronger IP_i is.

Step 4. Keep the best N_{imp} colonies as the imperialists and set the power of each imperialist as follows:

$$IP_i = OF \tag{11}$$

Step 5. Assign the colonies to each imperialist according to calculated IP_i.

Step 6. Move the colonies toward their relevant imperialist using crossover and mutation operators.

Step 7. Exchange the position of a colony and the imperialist if it is stronger ($CP_c > IP_i$).

Step 8. Compute the empire's power, i.e. EP_i for all empires as follows:

$$EP_i = \frac{1}{N_{E_i}} \times (w_1 \times IP_i + w_2 \times \sum_{c \in E_i} CP_c) \tag{12}$$

where w_1 and w_2 are weighting factors which are adaptively selected.

Step 9. Pick the weakest colony and give it to one of the best empires (select the destination empire probabilistically based on its power (EP_i).

Step 10. Eliminate the empire that has no colony.

Step 11. If more than one empire remained then go to Step. 6

Step 12. End.

IV. Simulation Results

The proposed ICA methodology is programmed in MATLAB running on an Intel®Core™2 Duo Processor T5300 (1.73 GHz) PC with 1 GB RAM. It is applied on a distribution system to demonstrate its abilities. The distribution network under study is a 11-kV, 69-bus system as depicted in Fig.2.

The technical data of this network can be found in [13]. All DG units are assumed to operate with constant power factor equal to 0.9 lag. The loss reduction incentive, i.e. ψ, and network deferral incentive, i.e. γ, are highly dependent on the system under study but here for comparing the proposed method with the other published results, these are assumed to be 48 $\frac{£}{MWh}$ and 2.5 $\frac{£}{kW}/year$ [13]–[15], respectively. The thermal capacity of lines, i.e. $\overline{I}_{\ell}$, are assumed to be 3 MVA. The other simulation parameters are provided in Table. I.

The active loss of the network is 0.228 MW when no DG units exists in the network, i.e. $loss^{nodg}$. The simulations are done for different number of DG units (three, five, seven and nine) and the results obtained by proposed ICA method.

A. Determination of parameters for ICA

In this section the influence of ICA parameters on average total incentives are investigated (after 100 trials). The following procedure has been adopted to calculate optimum value of the mutation and crossover probabilities. Different colony sizes, i.e., N_c, tried were 50, 80, 100, 150 and 200. For each colony size the crossover and mutation probabilities are increased from 0.1 to 0.9 in steps of 0.1 as described in Table II. Performance the proposed ICA is evaluated for all the above-mentioned combinations. 100 independent trials have been made with 200 iterations per trial. The performance of the ICA also depends on number of colonies. In Table II the performance of the ICA is checked also for different number of colonies. Based on the average total incentives obtained for different values of parameters given in Table II. This total incentive is more than the previously reported best result of 11.588 $£/h$ [21]. After a number of careful experimentation, following optimum values of ICA parameters have finally been settled: $N_c = 100$; crossover probability = 0.6, mutation probability=0.2 .

B. Comparing with other methods

The result obtained by proposed ICA method is compared with those of other methods: For classical method, the model is solved in Generalized Algebraic Modeling Systems (GAMS) [22], which is a highlevel programming platform, using DIscrete COntinuous OPTimization (DICOPT) solver. The evolutionary methods include Ordinal Optimization (OO) [14], GA-OPF [13], Particle Swarm Optimization (PSO) [23], pure Genetic Algorithm (GA) [24], Immune Algorithm [25] and Immune Genetic Algorithm (IGA) [21]. The optimal sizing and placement schemes of each method are given in Table.III to VI, for different number of DG units. Execution time complexity of each optimization method is very important for its application to real systems. The execution time of the proposed ICA is compared with other methods in Table.VII. This table presents a comparison among the results of the proposed algorithm ICA and other methods for 100 random trials. In Table.VII, the best and the worst solutions of the maximized objective function (total incentives) are are also given. Comparison of the best and worst solutions of the proposed optimization algorithm (ICA) with the corresponding those of the other methods confirms the effectiveness of the proposed method. Additionally, Table.VII provides the standard deviation and average value of the objective function, based on the proposed method and the other ones. This would show the convergence characteristics of the proposed ICA compared to other methods.

The average value of objective function in the proposed ICA method is greater than other analyzed methods while it has lower standard deviation. This means that the ICA is more robust comparing to other heuristic methods like GA-OPF, OO, PSO, GA, Immune and Immune-GA . The ICA uses the features of GA (mutation and crossover) to avoid trapping into a local optimum. Finally, the running time of the proposed ICA method, given in the last column of Table. VII, is less than GA-OPF, GA, PSO, Immune, IGA. The best solution of ICA is also better than the the solution found by GAMS/DICOPT (classical method). This is because of the inherent mixed integer nonlinear nature of the problem which makes it hard for classical methods to find the global optimum for a given solution. The classical methods are very sensitive to the initial starting points assigned to the variables specially in MINLP problems. The main drawback of the proposed method is that there is no proof for finding the global optimum solution in a given mixed integer non-linear problem. This problem also exists in classical methods because they are very sensitive to the starting point of the decision variables (initial values). Another drawback lies in the computational burden and running time that would inevitably increase for a larger distribution system (like other heuristic algorithms). It was already demonstrated in Table. VII that the running time of ICA is more than GAMS method. It should be noted that although this computation is off-line and will not be a serious problem for planner but can be reduced by using fast distribution load flow techniques [26] proposed in the literature.

V. Conclusion

This paper proposes an Imperialist Competition Algorithm for optimal placement of DG units. The defined objective function is the total incentives received by DNO due to active loss reduction and network investment deferral. The proposed optimization method is applied to a distribution network to demonstrate its flexibility and effectiveness. The simulation results show that the ICA possesses better convergence characteristics and robustness compared to other heuristic methods. It is also clear from the results of different trials that implementing the ICA gives the solutions with higher quality, computational efficiency compared to other methods. The proposed method is not only useful when the DNO performs the DG placement and sizing but also when other non-DNO entities perform DG investment. In such cases, the DNO can even share the benefits with DG developers to reach into a win-win strategy.

List of Symbols and Abbreviations

Indices

i, j	Bus
ℓ	Feeder

Constants

γ	Network investment deferral incentive
ψ	Active loss reduction incentive

Variables

P_i^D	Active power demand in bus i
P_i^{dg}	Active power injected by a dg in bus i
Y_{ij}	Admittance magnitude between bus i and j
θ_{ij}	Admittance angle between bus i and j
S_i^{dg}	Apparent power of dg installed in bus i
$P_{i,base}^D$	Base active power demand in bus i
$Q_{i,base}^D$	Base reactive power demand in bus i
$S_{i,base}^D$	Base apparent power demand in bus i
I_ℓ	Current magnitude of ℓ^{th} feeder
CP_c	Power of c^{th} colony
IP_i	Power of i^{th} imperialist
EP_i	Power of i^{th} empire
V_{min}	Lower operation limit of voltage
$\overline{P}_{lim}^{dg}$	Maximum operating limit of a dg
P_i^{net}	Net active power injected to bus i
Q_i^{net}	Net reactive power injected to bus i
N_b	Number of buses in the network
N_c	Number of colonies
N_{E_i}	Number of colonies in i^{th} empire
$\cos\varphi^{dg}$	Power factor of a dg
Q_i^{dg}	Reactive power injected by a dg in bus i
Q_i^D	Reactive power demand in bus i
$\overline{I}_\ell$	Capacity limit of existing feeder ℓ
V_{max}	Upper operation limit of voltage

V_i Voltage magnitude in bus i

δ_i Voltage angle in bus i

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List of Figure Captions

TABLE I

DATA USED IN THE STUDY

Parameter	Unit	Value
N_{imp}		10
w_1		0.8
w_2		0.2
V_{max}	Pu	1.06
V_{min}	Pu	0.94
Maximum iteration		200

TABLE II

INFLUENCE OF ICA PARAMETERS ON AVERAGE TOTAL INCENTIVES IN 9 DG CASE (AFTER 100 TRIALS).

N_c	Mutation probability	Crossover probability								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
50	0.1	11.018	11.027	10.983	10.975	11.039	10.976	10.961	10.978	10.973
	0.2	11.033	11.019	10.988	10.997	11.003	11.015	11.032	11.020	10.999
	0.3	10.987	10.977	10.957	10.959	10.978	10.960	11.002	11.010	11.028
	0.4	10.980	10.973	11.045	11.006	10.957	10.992	11.013	11.049	10.974
	0.5	11.027	11.031	11.010	11.043	10.990	10.955	11.026	10.951	10.988
	0.6	10.969	10.978	10.986	10.974	11.006	10.984	11.006	10.971	11.020
	0.7	10.952	10.951	10.965	10.957	11.029	11.027	10.962	11.036	11.022
	0.8	10.972	10.954	10.984	11.013	11.029	11.046	11.000	10.997	11.046
	0.9	11.003	10.980	10.969	10.986	10.975	11.028	10.962	10.950	11.012
80	0.1	11.019	11.029	10.984	10.976	11.040	10.977	10.962	10.979	10.974
	0.2	11.034	11.020	10.989	10.998	11.004	11.016	11.033	11.021	11.000
	0.3	10.989	10.978	10.958	10.961	10.980	10.961	11.003	11.011	11.030
	0.4	10.981	10.974	11.046	11.007	10.958	10.993	11.014	11.050	10.975
	0.5	11.028	11.032	11.011	11.044	10.991	10.956	11.027	10.952	10.990
	0.6	10.971	10.979	10.987	10.975	11.007	10.985	11.007	10.972	11.021
	0.7	10.953	10.952	10.966	10.958	11.030	11.028	10.963	11.037	11.023
	0.8	10.973	10.955	10.985	11.014	11.030	11.047	11.001	10.998	11.047
	0.9	11.005	10.982	10.970	10.987	10.976	11.029	10.963	10.951	11.013
100	0.1	11.020	11.030	10.986	10.977	11.041	10.978	10.963	10.980	10.975
	0.2	11.035	11.021	10.990	10.999	11.005	**11.501**	11.034	11.022	11.001
	0.3	10.990	10.979	10.959	10.962	10.981	10.962	11.004	11.013	11.031
	0.4	10.982	10.975	11.047	11.008	10.960	10.994	11.015	11.051	10.976
	0.5	11.129	11.034	11.012	11.045	10.993	10.957	11.028	10.953	10.991
	0.6	10.972	10.980	10.988	10.977	11.009	10.987	11.008	10.973	11.022
	0.7	10.954	10.953	10.968	10.960	11.031	11.129	10.964	11.038	11.124
	0.8	10.974	10.956	10.986	11.015	11.031	11.048	11.002	10.999	11.048
	0.9	11.006	10.983	10.971	10.988	10.977	11.031	10.964	10.953	11.014
150	0.1	11.022	11.131	10.987	10.978	11.042	10.979	10.964	10.981	10.976
	0.2	11.037	11.022	10.991	11.000	11.006	10.944	11.035	11.023	11.102
	0.3	10.991	10.980	10.960	10.963	10.982	10.963	11.005	11.014	11.032
	0.4	10.983	10.976	11.048	11.109	10.961	10.995	11.216	11.052	10.977
	0.5	11.230	11.035	11.013	11.047	10.994	10.958	11.029	10.954	10.992
	0.6	10.973	10.981	10.990	10.978	11.010	10.988	11.010	10.974	11.023
	0.7	10.955	10.954	10.969	10.961	11.033	11.030	10.965	11.039	11.025
	0.8	10.975	10.957	10.987	11.016	11.032	11.049	11.003	11.420	11.049
	0.9	11.007	10.984	10.972	10.989	10.978	11.032	10.965	10.954	11.015

TABLE III

DG LOCATION AND CAPACITIES FOR 3 DG UNITS

	DG capacity in MW							
Bus	GA-OPF [13]	OO [14]	Immune [25]	PSO [23]	GA [24]	GAMS	IGA [21]	ICA
16				1.502				
17						1.403		
24			0.934					
25					0.872			
26	0.738	0.738					0.738	0.850
31			2.000	2.000				
35	1.037	1.037				1.175	1.037	1.186
39					1.410			
60					1.618			
61			1.049	1.049				
62	0.887	0.887				0.982	0.887	1.000
loss incentive	7.582	7.582	6.400	5.209	4.106	6.787	7.582	7.535
Capincentive	0.762	0.762	1.023	1.169	1.002	0.914	0.762	0.869
Total	8.344	8.344	7.423	6.378	5.108	7.701	8.344	**8.404**

TABLE IV

DG LOCATION AND CAPACITIES FOR 5 DG UNITS

	DG capacity in MW							
Bus	GA-OPF [13]	OO [14]	Immune [25]	PSO [23]	GA [24]	GAMS	IGA [21]	ICA
4	0.942	0.942				1.042	0.898	1.059
11					0.713			
15				0.454				
17						1.403		
18					0.826			
19				0.681				
24							0.758	
26	0.760	0.760						0.850
29			0.676					
35	0.763			0.842		0.842		
40	0.709	0.807		0.798	1.144	0.798		0.873
44					0.131			
48							0.642	0.717
49		0.577						
50			0.792					
55			0.518				0.782	
62	0.890	0.890		0.982	0.982	0.982	0.885	0.990
65			0.592					
68			0.584					
loss incentive	9.419	9.457	8.491	8.013	7.316	8.725	9.479	9.438
Capincentive	1.163	1.138	0.812	0.965	0.975	1.302	1.135	1.284
Total	10.582	10.595	9.303	8.978	8.291	10.027	10.614	**10.722**

TABLE V

DG LOCATION AND CAPACITIES FOR 7 DG UNITS

	DG capacity in MW							
Bus	GA-OPF [13]	OO [14]	Immune [25]	PSO [23]	GA [24]	GAMS	IGA [21]	ICA
2					1.100			
3				1.100				
4		0.942					1.047	0.998
5	0.633		0.973					
10						0.602		
13	0.268					0.183		
14						0.076		
16					0.494			
17							0.675	0.686
18				0.210				
19				0.213	0.245			
21			0.259					
23			0.184					
24			0.733					
25	0.730							
26		0.760				0.841		
27				0.722	0.684		0.675	0.676
30		1.141						
32				1.014				
35	0.763		0.842	0.762		0.842		
40	0.721	0.720	0.798			0.798	0.870	0.871
48							0.712	0.719
49		0.546			0.714			
50					0.165			
57	0.795							
58		0.704					0.814	0.811
62		0.718						
65	0.652		0.910	0.910	0.910	0.910	0.737	0.750
loss incentive	9.869	9.646	9.747	1.266	8.358	1.092	9.859	9.837
Capincentive	1.305	1.583	1.207	9.433	1.108	9.864	1.424	1.577
Total	11.174	11.229	10.954	10.699	9.466	10.956	11.283	**11.414**

TABLE VI

DG LOCATION AND CAPACITIES FOR 9 DG UNITS

	DG capacity in MW							
Bus	GA-OPF [13]	OO [14]	Immune [25]	PSO [23]	GA [24]	GAMS	IGA [21]	ICA
2						0.880		
4	0.468	0.702	0.782				0.673	0.996
6	0.231		0.257					
12				0.646				
13	0.243	0.243				0.459	0.249	
16				0.675				
17		0.595						0.752
21	0.272						0.270	
24			0.326			0.326		
25			0.159	0.399		0.159		
26		0.634						
27	0.677		0.437			0.437	0.673	0.645
28				0.225				
29				0.125	0.676			
30		1.141					1.026	1.258
31					0.387			
32					0.105			
34			0.435					
35	0.763			0.842	0.762	0.985		0.496
36			0.444					
40	0.721	0.720	0.779	0.667	0.661		0.692	
41								0.498
44				0.131				
46						0.446		
48							0.606	
49		0.546						
50								0.406
57	0.747					0.884		
58		0.704					0.729	0.855
62	0.707	0.718	0.982					
63				0.906		0.709		
65							0.675	0.730
66					0.844			
67					0.029			
68					0.534			
69					0.049			
loss incentive	10.048	9.852	9.983	9.611	9.227	9.904	9.987	9.769
Capincentive	1.382	1.718	1.182	1.186	1.040	1.358	1.601	1.899
Total	11.430	11.570	11.165	10.797	10.267	11.262	11.588	**11.669**

TABLE VII

COMPUTATIONAL PERFORMANCE COMPARISON BETWEEN THE PROPOSED ICA AND OTHER METHODS FOR 100 TRIALS

# of DG	Method	Average $£h^{-1}$	Standard deviation $£h^{-1}$	Worst solution $£h^{-1}$	Best solution $£h^{-1}$	Running time (s)
3	GA-OPF [13]	7.81	0.28	7.17	8.34	4572
	OO [14]	8.12	0.21	7.14	8.34	3002
	PSO [23]	6.35	0.25	6.04	6.38	4253
	GA [24]	5.10	0.18	4.66	5.11	4426
	Immune [25]	7.48	0.26	6.77	7.42	4382
	GAMS	7.70	0.00	7.70	7.70	6
	IGA [21]	8.19	0.22	7.42	8.34	4151
	ICA	8.27	0.16	8.04	**8.40**	3010
5	GA-OPF [13]	10.12	0.31	8.83	10.58	9864
	OO [14]	10.16	0.36	9.34	10.60	7114
	PSO [23]	8.86	0.30	8.42	8.98	7522
	GA [24]	8.07	0.32	7.68	8.29	7675
	Immune [25]	9.16	0.28	8.60	9.30	7847
	GAMS	10.03	0.00	10.03	10.03	11
	IGA [21]	10.36	0.37	9.45	10.61	7324
	ICA	10.46	0.22	9.97	**10.72**	5750
7	GA-OPF [13]	10.55	0.31	9.34	11.17	7521
	OO [14]	10.82	0.32	10.08	11.23	6966
	PSO [23]	10.67	0.33	9.68	10.70	7339
	GA [24]	9.21	0.30	8.83	9.47	7696
	Immune [25]	10.68	0.42	10.16	10.95	7766
	GAMS	10.96	0.00	10.96	10.96	16
	IGA [21]	10.99	0.30	10.00	11.28	7238
	ICA	11.10	0.23	11.05	**11.41**	6045
9	GA-OPF [13]	10.60	0.32	9.40	11.43	13780
	OO [14]	11.19	0.36	10.14	11.57	10069
	PSO [23]	10.67	0.40	10.23	10.80	12281
	GA [24]	10.33	0.31	9.54	10.27	11926
	Immune [25]	10.75	0.39	10.55	11.17	11989
	GAMS	11.26	0.00	11.26	11.26	23
	IGA [21]	11.39	0.40	10.34	11.59	11925
	ICA	11.50	0.25	10.72	**11.67**	8742

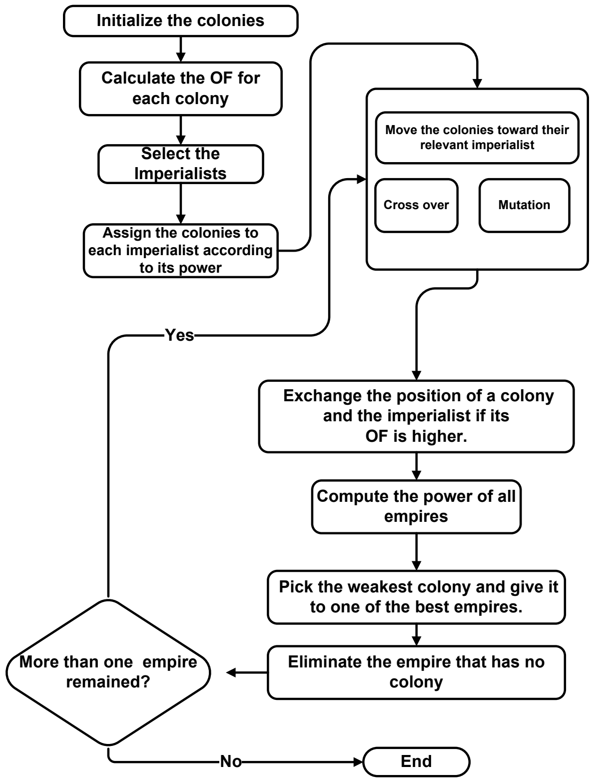

Fig. 1. The flowchart of proposed Imperialist Competition Algorithm

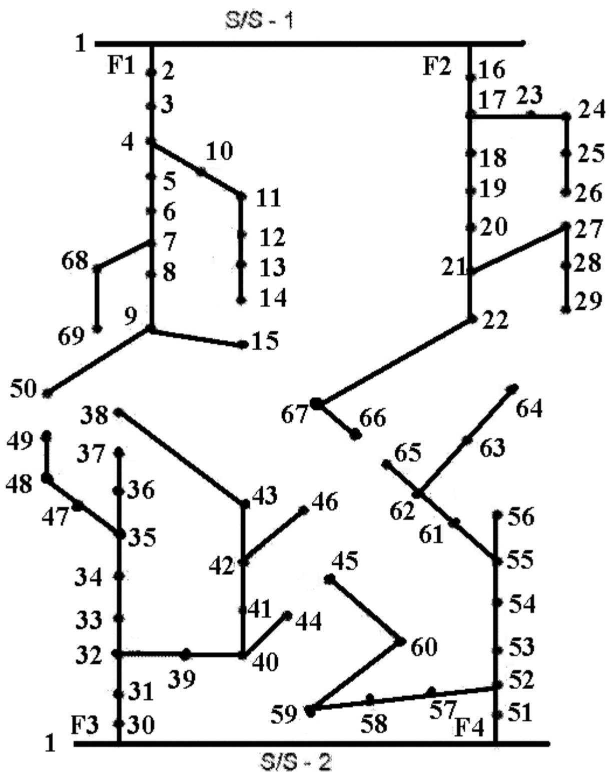

Fig. 2. Single-line diagram of the 69-bus distribution network