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OPTIMAL DG AND CAPACITOR ALLOCATION IN DISTRIBUTION SYSTEMS USING DICA

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Abstract

In this paper, a method was presented based on Discrete Imperialistic Competition Algorithm (DICA) for optimal placement of Distributed Generation (DG) and shunt capacitors. In this paper a new assimilation mechanism in introduced for DICA. Developments of various technologies of distributed generation and their cost-effectiveness have increased the use of these resources. Shunt capacitors, as reactive power compensators, are also the equipment that inject reactive power to distribution network in order to improve voltage profile release a part of the network capacity and also reduce the losses. The objective function was defined based on the reduction of active power losses. The performance of the proposed method tested on two, 33-bus and 69-bus IEEE standard systems. In spite of the objective function defined based on active losses reduction, the results demonstrated that, voltage profile improved and reactive losses greatly reduced after optimal DG and capacitor allocation.

Keywords: Distributed generation, Shunt capacitor, Optimal placement, Loss reduction, DICA.

1. Introduction

Distribution networks have the highest rate of losses in power systems. Losses in distribution networks not only cause electrical energy loss but also occupy capacity of transformers and lines. Increasingly losses at peak times of load consumption, increase the investment need in developing power plants and transmission networks. One of the methods for reducing losses is to use distributed generation resources and shunt compensation capacitors.

Nomenclatures

C_i^{Cap}	i^{th} Capacitor size
I_i	Current of i^{th} line, A
N_C	*Number of capacitors*
N_{DG}	Number of DGs
P_{DG}	Active powers of DGs
P_d	Total active power demand of network loads
P_{loss}	Active power losses of the network
P_{sys}	Active powers injected to the network by sub-transmission network
pf_i^{DG}	i^{th} DG power factor
Q_{Cap}	Injected reactive power of shunt capacitors
Q_{DG}	Reactive powers of DGs
Q_d	Total reactive power demand of network loads
Q_{loss}	Reactive power losses of the network
Q_{sys}	Reactive powers injected to the network by sub-transmission network
r_i	Resistance of i^{th} line, ohm
S_i^{DG}	i^{th} DG size
TC_n	Absolute total power of the n^{th} empire
x	Random variable

Shunt compensation capacitors are among the first equipment used in electricity network, in order to improve voltage profile. The advantages of capacitors include reducing active losses, reducing reactive losses, releasing capacity of transformers and lines, improving power coefficient and maintaining voltage within the specified allowed range. To take advantage of the mentioned cases, the capacitors should be used in optimal locations with optimal sizes. For optimal placement of a capacitor in electricity networks, different methods have been presented [1-4].

With the development of technologies related to distributed generation resources and utilizing inexpensive renewable energies, the penetration percent of these energy generation resources in networks is increasing. Using distributed generation resources provides many advantages for the network and its operator, some of which include reducing active losses, reducing reactive losses, postponing investment, increasing reliability, peak clipping, reducing cost of electrical energy, improving voltage profile, etc. Optimal usage of the mentioned advantages depends on placing and determining the optimal size of these resources. Various methods have been proposed for optimal placement of distributed generation resources with different objective functions [5-8].

Considering the advantages of using distributed generation and capacitors, simultaneous use of these two provides multiple capabilities for electrical energy distribution systems. Due to their different working bases, simultaneous optimal placement of these two has different results from their independent placement [9]. Various methods have been proposed for optimal placement of DG and shunt capacitors. [9] proposed two methods for optimal capacitor and DG placement. The objective considered in [9] was voltage profile. A numerical method for the identification of the target voltage support zones is proposed by reducing the large search space in [10] for optimal DG and capacitor placement. The optimal DG and capacitor placement problem solved using Genetic Algorithm (GA) in [11]. In [12], a genetic algorithm (GA) is proposed for simultaneous power quality improvement, optimal placement and sizing of fixed capacitor banks in radial distribution networks with nonlinear loads and distributed generation (DG) imposing voltage–current harmonics. In [13], simultaneous placement of distributed generation (DG) and capacitor is considered in radial distribution network with different load levels. The objective of the problem was voltage stability index. Authors in [14], proposed a strategy for optimal capacitor and DG placement in radial networks based for reactive and active losses reduction.

In this study, the basis of placement was reduction in losses of distribution network, considering the technical and electrical constraints of the network. In this regard, the Discrete Imperialistic Competition Algorithm was introduced. ICA is an evolutionary computing algorithm and its process is based on social evolution and colonial competitive between the imperialist in order to increase strength and improve their positions [15]. ICA validity has been proved by testing on different benchmark functions and optimization problems, in power systems [16-18].

In this paper, simulations were done on 33-bus and 69-bus IEEE standard networks. First, optimal placement of capacitor and distributed generation was separately done and then their simultaneous placement was performed at normal and peak load conditions. The results showed loss reduction and voltage profile improvement. These results demonstrated the effectiveness of ICA for solving the problem of optimal placement of capacitor and distributed generation, both simultaneously and independently.

2. Problem Formulation

One of the main advantages of using compensating capacitors and distributed generation resources is to reduce losses in electricity energy distribution networks as much as possible, considering equality and inequality constraints of the network. In other words, the problem can be stated as finding the location and size of shunt capacitor and DGs by maximum reduction of the active power loss. The applied load flow method has a direct effect on the accuracy and reliability of responses. In fact, main core of the problem solving is the plan for load flow in the presence of capacitor and DGs. Therefore, backward and forward load flow was used in this paper.

Optimal placement problem is one example of mixed integer non-linear optimization. Formulas and constraints of this problem are as follows. In this case, location of capacitor and DG, size of capacitor and DGs and power factor of DG are optimization variables. Load flow was performed in each mode in order to investigate the losses amount and electrical and technical constraints in the network.

2.1. The objective function

As mentioned before, the objective function was based on reduction of active power losses in the network. The objective function is as follows:

$$Objective \quad Function : \min \sum_{i=0}^{n} (I_i)^2 . r_i \tag{1}$$

where I_i and r_i are current and resistance of i^{th} line. In fact, sum of active power losses of lines, between buses, are considered as total losses of the distribution network.

2.2. Active and reactive power balance

To maintain balance between generation power of the network and its power consumption, the following relation should be established:

$$P_{sys} + P_{DG} = P_d + P_{loss} \tag{2}$$

$$Q_{sys} + Q_{DG} + Q_{Cap} = Q_d + Q_{loss} \tag{3}$$

where P_{sys} and Q_{sys} are active and reactive powers, respectively, which are injected to the desired distribution network by sub-transmission network. P_{DG} and Q_{DG} are active and reactive powers of DGs. P_d and Q_d are total power demand of network loads. P_{loss} and Q_{loss} are both active and reactive power losses of the network. Q_{Cap} is the injected reactive power of shunt capacitors to the distribution network

2.3. Constraint of voltage's allowed range

All power systems, including distribution network, should be operated in a voltage within the allowed range. In this article, the allowed deviation was equal to 5% of the nominal voltage of the network.

$$0.95_{(Pu)} \le V_i^{sys} \le 1.05_{(Pu)} \tag{4}$$

2.4. Constraints of line capacity

All the lines available in the network had thermal limitation. In fact, the current passing through the lines should not exceed its allowed thermal rate. The thermal constraint is as follows:

$$|I_i| \le |I_i^{rated}| \tag{5}$$

2.5. Limits of DG and capacitor size

Due to technical and electrical limitations in terms of capacity of compensation capacitor components and DGs, it is not possible to use these devices with any capacity. In this article, considering that DGs and capacitors are not available in every size, practically, standard implementable discrete values were used. According to this issue, the obtained results were reliable and practically applicable. For instance, for capacity of distributed generation resources, discrete values were considered with change of 25(kW) between 10% and 80% of total network load. The amount of power factor of DGs was considered between 0.8(lag) to 0.8(lead) with 0.05 intervals [5]. The constraints are as follows:

$$S_{\min}^{DG} \le S_i^{DG} \le S_{\max}^{DG} \tag{6}$$

$$pf_{\min}^{DG} \le pf_i^{DG} \le pf_{\max}^{DG} \tag{7}$$

$$C_{\min}^{Cap} \le C_i^{Cap} \le C_{\max}^{Cap} \tag{8}$$

3. Discrete Imperialistic Competition Algorithm (DICA)

For the Imperialistic Competition Algorithm (ICA) is an optimization algorithm based on imperialistic competition between colonizers and their colonies [15]. Like other evolutionary algorithms, this algorithm begins with an initial population, each of which is called a country. A certain number of initial countries which have more power and, in other words, less amount of objective function, are selected as initial emperors. The rest of the countries as colonies are distributed between these empires based on their power, in order to found the initial empires. After this step, the colonies begin to move toward their imperialists and go to new locations. This place is probably even better than the related imperialist and as a result the role of these two changes. Afterwards, competition between different empires increases in terms of strengthening their power. The colonial with more power seizes the colonies of other empires with less power and increases its overall power which is a function of its own and colonies position. This procedure is performed several times until only one empire is left in the world, which is the optimal solution with maximum power or minimum amount of cost function.

In this algorithm, each country has some variables. Optimization variables determine the country location in the optimization space. Power of each country, which is in reverse relationship with the amount of objective function (losses amount) depends on the values of optimization variable. In this paper, these variables included location, capacity and power factor of DGs and shunt compensation capacitors size and locations. In each new position in the optimization space, load flow was run in the presence of distributed generation resources and compensation capacitors in order to calculate current values in different lines and, as a result, the loss quantity of the whole network. In this paper, ICA was introduced and implemented in a discrete way, so that of algorithm output for size and power factor of DGs and compensators would be reliable and practically applicable in real distribution networks. Figure 1 demonstrates the complete flowchart of DICA. Considering the evolutionary mechanism of this algorithm, in comparison with other methods, it can quickly converge to the optimal value. In this paper a new assimilation mechanism is proposed for DICA. All the results were obtained after 50 independent runs. In all cases the DICA converges to same optimal results. Since the results had the same responses and absolute minimums for several times of independent runs, their responses could be used as reliable values. Details of the proposed algorithm are explained in the proceeding sub-sections.

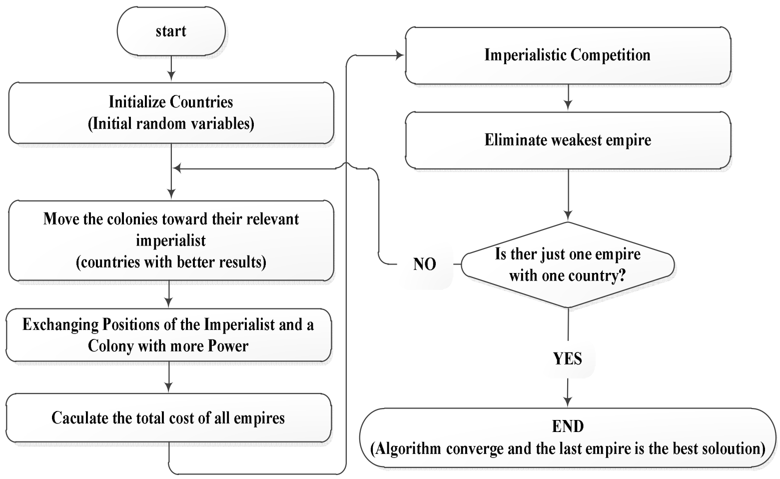

Fig. 1. Flowchart of DICA.

3.1. The generating initial empires

The goal of all optimization algorithms is to find optimal solution, regarding problem variables. In the DICA there is an array of discrete variables which have to be optimized. In this paper the array variables are include buses numbers, size of DG and capacitors and p.f. of DG units. Figure 2 shows a country structure.

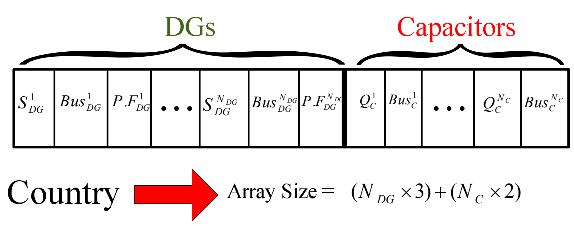

Fig. 2. A Country Structure in Optima Placement Problem.

To start the optimization process, initial countries (population) are generated. Then some of the most powerful countries are chosen as imperialists to form the initial empires. The number of initial empires is assumed to be 10% of total initial countries as advised in [15]. Once the initial countries are formed, colonies are divided among imperialists based on their power, in proportion to the inverse of their cost values.

3.2. Moving the colonies of an empire toward the imperialist

At this stage, imperialists start to increase their colonies power. In the ICA, this mechanism is modeled by moving colonies toward their relevant imperialists, as shown in Fig. 3. In the continuous version of ICA, colony moves toward imperialist by $\boldsymbol{x}$ units as shown in Fig. 3. The variable x is a random variable with pre-defined probability distribution function. In the proposed discrete binary ICA, the assimilation mechanism is different from that of the continuous version.

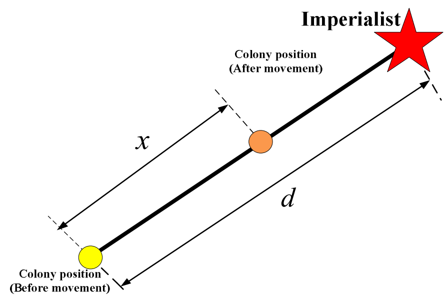

Fig. 3. Movement of Colonies toward Relevant Imperialist (Conventional).

In conventional continues version of ICA, the variables could get any values, while in DICA variables should be a certain numbers. In this paper a new assimilation mechanism is introduced for assimilation mechanism.

Figure 4 shows the new assimilation mechanism. In this mechanism, a feasible space is defined between imperialist and colony positions. The feasible space contains some certain positions. The colony moves toward imperialist by transferring from its current place to new one. The probabilities of all locations are equal as a new place for colony.

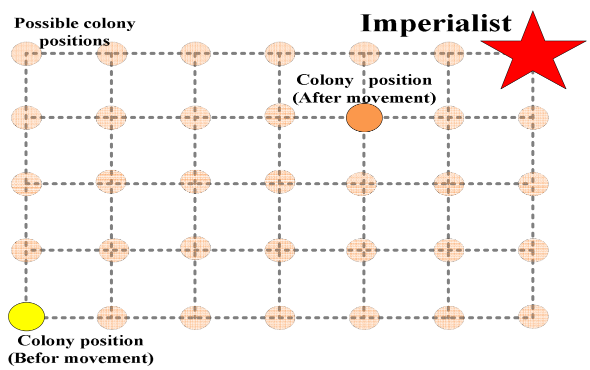

Fig. 4. Movement of Colonies toward Relevant Imperialist (New Assimilation Mechanism).

3.3. Exchanging positions of the imperialist and a colony

After the assimilation stage, a colony may reach a position with less cost than its relevant imperialist. In such a condition, the roles exchanged and the colony becomes the new imperialist and the previous imperialist changes to a colony. After this exchanging process, the colonies start to move toward this new imperialist.

3.4. Total power of an empire

As shown in the flowchart of Fig. 2, in this part total power of each empire should be calculated. The total power is affected by imperialist and colonies powers. However, colonies have less effect on the total power. Total power is calculated as follows [15]:

$$TC_n = Cost\,(imperialist_n) + \xi\; mean\,\{Cost\,(colonies\ of\ \ empire_n)\} \tag{9}$$

where TC_n is the absolute total power of the n^{th} empire and ξ is a positive factor which is assumed to be 0.2 in this paper. In fact, ξ depicts the role of colonies in calculating the absolute power of an empire.

3.5. Imperialistic competition

This stage is the main part of DICA. In this stage, all empires try to possess colonies of other imperialists and improve their power by controlling them. The Imperialistic competition gradually causes powerful empires to possess more colonies and improve their power. On the other hand, weak empires lose their colonies progressively. This process is modeled by selecting the weakest colony of the weakest empire and a competition among other powerful ones to take its possession. In this part the chance of each empire to take control of this weak colony, is in proportion to its total power, which was calculated in previous stage. In other words, the probability of possessing the colony by most powerful empire is more than others [15].

3.6. Eliminating the powerless empires

After the Imperialistic Competition, gradually some of weak imperialists may lose all their colonies and have no more colonies. In this condition, this powerless empire collapses and it is eliminated.

3.7. Convergence

After several iterations, which is called decade in ICA, all the empires will collapse and all the colonies are under control of a most powerful imperialist. In other words, all the colonies and imperialist are in the same imperial. The algorithm converges, when all colonies move toward imperialist and be in same position with emperor. In such condition, algorithm stops and the mentioned position is the best answer. In other words, the location of this superpower is the best answer and the optimum result.

4. Simulations and Results

In this section, the proposed algorithm is applied on test cases in different conditions. These tests were applied on 67-bus and 33-bus IEEE standard systems, In order to demonstrate capability of the proposed method in various conditions and topologies. Figures 5 and 6 demonstrate one-line diagram of 33-bus and 69-bus networks, respectively. Tables 1 and 2 show the characteristics of the mentioned networks before capacitor and distributed generation placement. In Sections 3.2 and 3.3, besides normal load conditions, the problem was solved in the network's peak load condition, using the proposed method.

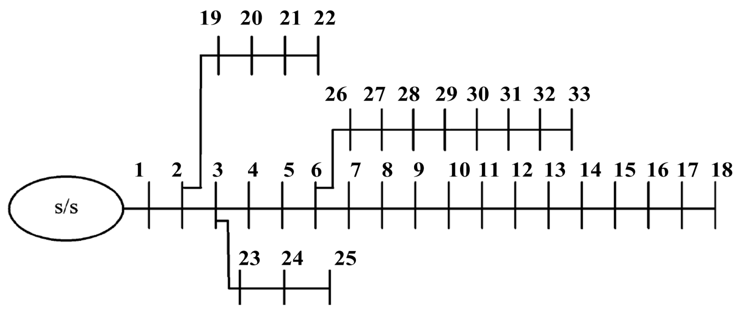

Fig. 5. IEEE 33-Bus Test System.

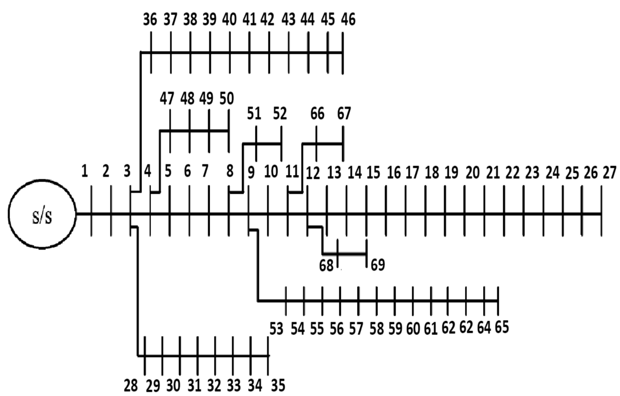

Fig. 6. IEEE 69-Bus Test System.

4.1. Capacitor placement in 69-bus system

In this section, optimal placement problem for shunt capacitor in the 69-bus standard network is solved. In this system, under normal load conditions, voltage of some buses was less than the allowed amount in basic mode. Hence, adding compensation shunt capacitor in appropriate locations, reduced the losses and relocate voltage of buses inside the allowed range. The results showed that, although the objective function was based on maximum active losses reduction, the capacitor had considerable effect on reduction of reactive losses and improvement of voltage profiles.

In this section, capacitor placement was done with one, two and three capacitors. Table 3 demonstrates the optimal capacitor placement results in 69-bus system in normal load condition. The voltage amplitude was acceptable and within the allowed range after adding the capacitors. As shown in Table 3, one capacitor did not have significant effect on the amount of active losses and, considering the constraint of voltage limit, this single capacitor just cause the voltage to become allowed range. While two and three capacitors were located in the network, not only the voltage was within the specified allowed range, but also, losses decreased acceptably.

Table 1. Summary of the 69-Bus System Default Case (load scenario I, II).

Load scenario	I	II
$\sum kW \quad loss$	224.94	560.53
$\sum kVar \quad loss$	102.35	253.59
$\lvert V_{min}\rvert$, P.u.	0.9091	0.8559
$\lvert V_{max}\rvert$, P.u.	1.0000	1.0000
$\sum \lvert S_{Load}\rvert, KVA$	4660.20	6990.30

Table 2. Summary of the 33-Bus System Default Case.

System	33-bus
$\sum kW \quad loss$	211
$\sum kVar \quad loss$	143.03
$\lvert V_{min}\rvert$, P.u.	0.9038
$\lvert V_{max}\rvert$, P.u.	1.0000
$\sum \lvert S_{Load}\rvert, KVA$	4369.34

Table 3. Optimal Capacitor Placement Results (69-Bus).

Number of capacitors	1	2		3		
Optimum location	63	62	5	62	12	47
Capacitor size (kVar)	2625	2175	2100	2100	475	1700
Active losses (kW)	226	164		159		
Reactive losses (kVar)	101	75		73		
$\lvert V_{min}\rvert$ **(Pu)**	0.9591	0.9591		0.9500		
$\lvert V_{max}\rvert$ **(Pu)**	1.0000	1.0000		1.0000		

4.2. DG placement in two load scenarios

In this section, DGs are placed in 69-bus system. Besides solving the problem in normal load mode, the problem of optimal DG placement was solved in the peak mode. In the peak load mode, all network loads increased by 50%. In other words, the network load was considered 1.5 times of the system normal load mode. Table 4 demonstrates the results for both modes. Referring Table 4, active losses in normal and peak load modes reduced by 89% and 90%, respectively. After placing the DG unit in proper locations, besides reduction of active losses, reactive losses reduced considerably, system voltage profile, especially in peak load mode of the network, considerably improved and voltage of all buses was placed within the allowed range. Table 5 shows the comparison of the results of proposed algorithm with other methods for DG placement problem. As results depict, the proposed DICA has better results in comparison with other methods. In previous works, the constraints are not presented and applied completely. In [19, 20] the constraints of the generation capacity is not applied to the problem.

Table 4. Optimal DG Placement Results in Two Load Scenario (69-Bus).

Load scenario	I	II
Optimal DG location(bus)	61	b
Optimal p.f.	0.8 (lead)	0.8 (lead)
Optimal DG size(KVA)	2250	3250
$\sum kW \quad loss$	23.05	53.37
$\sum kVar \quad loss$	14.52	36.68
$\|V_{min}\|$, P.u.	0.9731	0.9583
$\|V_{max}\|$, P.u.	1.0000	1.0000

Table 5. Comparison of the Results of Proposed DICA with other Methods for DG Placement Problem.

Feeder system	69-bus(scenario 1)
Analytic [19]	62.9%
ABC [5]	63%
GA [20]	62.9%
Modified ABC [21]	63%
Proposed DICA	89%

4.3. Simultaneous DG and capacitor placement

Considering different structure and function of capacitor and distributed generation for reducing losses, simultaneous placement of these two had a different trend compared with previous modes. In this section, two capacitors, simultaneously with one DG unit, in 69-bus system in the normal load mode, and three shunt capacitors, simultaneously with one DG resource, in the peak load condition were placed with optimal sizes. Table 6 demonstrates the obtained results for two normal and peak load regimes of the network. As regard results, active power losses in this network reduced by about 92.5% and 93% for normal and peak loads, respectively. Figure 7 shows the voltage profile of distributed system, before and after simultaneous placement of capacitor and distributed generation resource in the peak load. Not only the buses' voltage was located within the allowed range, but also voltage profile was flat and had slight derivation from the amount of 1 (pu). In this mode, reactive losses of the network considerably reduced compared with the normal mode. According to increasingly growing usage of these resources, these results demonstrated the large effect of optimal placement and determining the optimal size of shunt compensation capacitors and distributed generation resources in obtaining the maximum efficiency.

Table 6. Optimal DG and Capacitor Placement Results in Two Load Scenario (69-Bus).

Load scenario	I		II		
Optimal DG location(bus)	61		61		
Optimal p. f.	0.85(lead)		0.9(lead)		
Optimal DG size(KVA)	2250		3075		
Optimum Capacitor location	11	20	64	17	66
Capacitor size (kVar)	350	250	450	350	550
Active losses (kW)	17.2		38.7		
Reactive losses (kVar)	12.01		27.2		
$\lvert V_{min} \rvert$, P.u.	0.9799		0.9671		
$\lvert V_{max} \rvert$, P.u.	1.0027		1.0007		

4.4. Simultaneous DG and capacitor placement in 33-bus system.

In this section, simultaneous optimal placement was performed for capacitor and distributed generation resource in 33 bus standard network. The results are presented in Table 7. Considering these results, the presented algorithm was able to solve the optimal placement problem in all networks with global optimum and acceptable results. In this case, active and reactive losses of the network were considerably reduced and buses' voltages were located in the allowed range with a relatively low deviation from the nominal amount.

Table 7. Optimal DG and Capacitor Placement Results in IEEE-30 Bus.

Optimal DG location(bus)	6		
Optimal p. f.	95(lead)		
Optimal DG size(KVA)	2500		
Optimum Capacitor location	13	30	24
Capacitor size (kVar)	275	750	300
Active losses (kW)	47.5		
Reactive losses (kVar)	38.9		
$\lvert V_{min} \rvert$, P.u.	0.9656		
$\lvert V_{max} \rvert$, P.u.	1.0004		

5. Result Analysis

Distributed generation resources and capacitors have positive effects on distribution system performance and efficiency. Optimal placement of these devices provides multiple positive advantages for beneficiaries. In this paper, the DICA was used to solve this problem. The advantages of solving this problem using the mentioned algorithm can be mentioned as follows:

5.1. Voltage profile

Among the tested cases, the 69-bus system in the peak load condition had the most unfavorable voltage profile, compared with others. Figure 7 demonstrates voltage profile of this network before and after simultaneous optimal placement of DG unit and shunt capacitors. Figure 7 shows that although the objective function was defined based on reduction of active losses, voltage profile was also greatly improved. All the voltages of busses were within the allowed range and the overall standard deviation was negligible compared with the basic mode, before the placement.

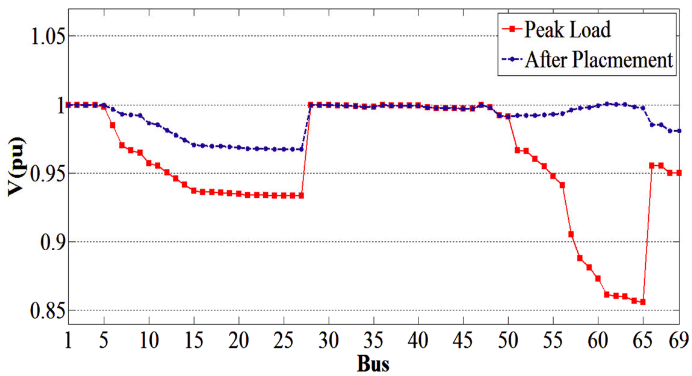

Fig. 7. Voltage Profile of 69-Bus System (Scenario II) before and after Placement.

5.2. Reduction in active losses

Considering the selection of active losses reduction as the objective function, the obtained results were the most optimal ones in terms of active loss of the distribution network. Figure 8 shows the losses amount in different modes. According to Fig. 8, in the presence of DG and capacitors, losses reduced less to about 17 kW.

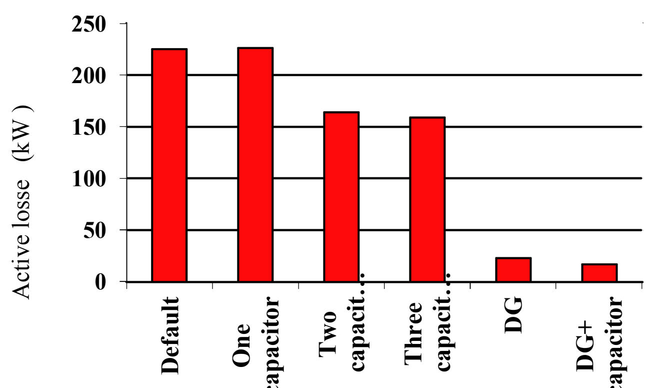

Fig. 8. Active Power Losses Comparison in Different Cases.

5.3. Reactive losses

Figure 9 shows the reactive power losses amount in different modes. The results show that reactive losses greatly reduced simultaneously with the active ones. After simultaneous optimal placement of distributed generation resources and capacitors, reactive losses decreased by 88%, 89% and 73% in normal and peak load of the 69-bus system and also normal load of 33-bus system, respectively.

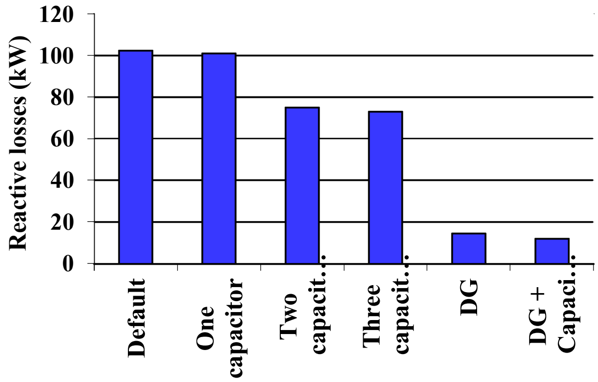

Fig. 9. Reactive Power Losses Comparison in Different Cases.

6. Discussion

This work presents a solution for optimal DG and shun capacitor placement, in radial distribution system, using DICA. Solving optimal placement problem using DICA has significant advantages over other algorithms. The following are some of important features:

- The algorithm is capable of solving DG and Capacitor placement problem in both independent and simultaneous conditions.
- The global optimum location and size and *p.f.* are obtained using DICA.
- The active losses reduce to minimum possible values after optimal placement, due to objective function which was based on active losses reduction.
- The voltage profile become flatter after optimal placement, also the objective was based on losses reduction.
- Reactive losses decrease up to 89% after optimal DG and capacitor placement.
- The proposed algorithm has capability of solving optimal DG and capacitor allocation problem in different systems.
- The results show the algorithm efficiency in optimal capacitor and DG placement solving problem in various load scenarios.
- Considering discrete values for size and *p.f.* of DG units and size of capacitors cause practically applicable results.

The results, in comparison with previous work, demonstrate the proposed algorithm efficiency in solving mix-integer placement problem and handling different constraints.

7. Conclusions

In this paper, an algorithm was introduced for loss reduction in distribution systems by optimal allocation of DG and capacitor using discrete imperialistic competition algorithm. The new DICA was proposed in this paper, with new assimilation mechanism. The results shows the proposed DICA converges to same optimal results after 50 independent runs, which prove the efficiency of proposed method in solving DG and capacitor placement. The objective function was considered based on active losses reduction. In all the simulations, technical and electrical constraints were considered, in order for the values to be reliable and practical. The proposed method was tested on the IEEE 69-bus standard test system in both normal load and peak load modes and also in the normal load condition of 33-bus standard system. The results not only demonstrated significant reduction in active losses, but also show the great improved of other parameters network. In this paper, discrete practical values were considered for capacitor and DG sizes, in order for the results to be practically applicable. The obtained results indicated capability of the proposed algorithm in solving non-linear mix-integer problem of optimal placement of capacitor and DG, both separately and simultaneously.

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