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MULTIOBJECTIVE PLACEMENT OF MULTIPLE DISTRIBUTED ENERGY RESOURCES IN DISTRIBUTION SYSTEM USING IMPERIALIST COMPETITIVE ALGORITHM (ICA)

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Abstract- Distributed Energy Resources (DERs) have been employed in the distributed systems to satisfy several objectives. This paper proposes a multi-objective approach to optimally determining the size and location of multiple DERs in the distribution system. In order to make the results more accurate and applicable DERs are considered with non-unity power factor. Loss reduction and reduction in power purchased from the electricity market, loss reduction in peak load hours and therefore reduction in upgrade investment deferral as well as improving voltage profile are considered as the objectives in this study. Considering these objectives in the optimization problem this paper presents a methodology that aims at the maximization of benefits from employment of DERs. The investment and operational costs of DERs are considered and the Imperialist Competitive Algorithm (ICA) is used to solve this complicated optimization problem. The effectiveness of the proposed method is demonstrated using IEEE 30-bus radial distribution test system and the results are discussed in detail. The obtained results are compared with those obtained by Particle Swarm Optimization (PSO) and Harmony Search Algorithm (HSA). The comparison illustrates that the proposed approach is capable of finding the best location and optimal size of multiple DERs that can effectively improve operational characteristic while reduce the operational costs in the distribution system.

Keywords: Distributed Energy Resources (DERs), Imperialist Competitive Algorithm, Loss Reduction, Voltage Profile Improvement.

I. INTRODUCTION

Distributed Energy Resources (DERs) are small generating units connected directly to the distribution network or on the customer side of the meter. Restructuring of power systems as well as the desire for reduction in greenhouse gas emissions and alleviation of global warming along with the increasing public awareness of environmental issues have caused an augmented interest in DERs, that includes distributed generation (DG) and energy storage devices.

Many benefits could be achieved by placement of DERs. However, these units if installed without thorough consideration could cause some difficulties in operation of distribution systems. As a result, the problem of optimal placement of the DERs needs special attentions as well as consideration of all factors in the planning stage. DERs are optimally located in the distribution system to defer or eliminate system need for upgrades, improve voltage profile, reduce the energy losses, reduce loss in peak load hours, and to improve system reliability [1].

The most important benefits of DER are modeled in [2] in form of economic terms to ease the evaluation of DER placement problem. Reference [3] proposed a set of indices for modeling and quantifying of technical benefits of DERs. The aim of the optimal DER placement is to determine best locations and size of DER units to optimize electrical distribution network operation and planning. Several models and methods have been suggested for the solving this complicated optimization problem.

An overview of the state of the art models and methods applied to the DER placement problem is proposed in [4], in which the applied approaches are analyzed and current and future research trends are classified. The typical DER placement problem deals with determination of optimum locations and size of DER units to be installed into existing distribution systems, subjected to network constraints, DER operation constraints, and financial constraints.

As a result, the DER placement is a complex mixed integer nonlinear optimization problem [4]. Being a very complicated problem, several approaches with different objectives have been applied to solve this problem. Analytical approaches were used in radial as well as meshed topologies of distribution systems [5], Dynamic Programming (DP) was applied to solve a DG placement model that maximizes profit of Distribution Network Operator (DNO) & considers different load conditions [6].

An Ordinal Optimization method is employed in [7] for specifying the locations and sizes of multiple DGs. However, the formulation of analytical methods could not simply be modified to also model some features of these systems, specially the multi-objective problem as well as objectives other than loss.

The other deficiency of analytical approaches is that these studies take the size of DER as total load size and in respect of the size of DER obtains the optimal location of DER in radial systems without optimizing its size [8]. Loss minimization is the objective of the most studies in this realm. The optimization tools for solving this problem are heuristic algorithms. Some heuristic techniques have been addressed like Genetic Algorithm (GA), Tabu Search (TS), Particle Swarm Optimization (PSO) as well as Simulated Annealing (SA).

Since there exist a necessity for more improvement to existing solution techniques, the hybrid models such as GA and Hereford Ranch Optimization Algorithm [9], Fuzzy-GA [10], Genetic-Based TS Algorithm [11] are experienced. Several benefits could be achieved by integrating DER with power systems. Therefore, multi-objective optimization problem of placement of DER units were proposed. Reference [12] proposed two multi-objective formulations based on the GA and a ε-constrained method as optimization method for the placement and sizing of DER in distribution networks.

The optimization process was a compromise between reduction in power losses, reliability improvement, and reduction in power to be purchased from the power market and minimization of the cost of network upgrading. A same problem was solved for a sub-transmission network using a classic optimization method, GA, and an innovative approach in [13]. In [14], multi-objective performance index function reflecting effect of DG insertion on real and reactive power losses of system, the voltage profile, and distribution line loading was proposed and GA has been used as optimization technique.

Reference [15] studied the placement of a single DG unit with pre-defined size where impact of placing DG at each node of system was thoroughly taken into account. The system indices including system losses, voltage profile, line-loading capacity and short-circuit level, were studied. In this paper, we focus on applying the Imperialist Competitive Algorithm (ICA), to find the location and size of the multiple DER units with the objectives of loss reduction, reliability improvement, expansion cost minimization and reduction of power purchased from electricity power market.

ICA, which is a novel evolutionary computational method has been used to solve many optimization problem. The potential of ICA in solving the complicated optimization problems in realm of power system has been demonstrated in [16-21]. Like most of heuristic methods, in order to find optimal solution, ICA does not need gradient of function in its optimization process, therefore, is suitable to solve problem which objective function is not convex and differentiable [21]. ICA is a heuristic method conceptualized from humans social evolution.

There are several constraints in DER placement problem. In the case of violation of such constraint, an appropriate penalty is added to the value of the objective function to avoid such solution. The obtained results are compared with those obtained by Particle Swarm Optimization (PSO) and Harmony Search Algorithm (HSA). The rest of the paper is organized as follows.

Section II gives an overview of Imperialist Competitive Algorithm. Proposed approach is presented in section III. The proposed scheme is applied on IEEE 30-bus radial distribution test system, and the results are presented and discussed in section IV. The conclusion remarks are drawn in section V.

II. IMPERIALIST COMPETITIVE ALGORITHM

Evolutionary optimization methods, inspired by natural processes, have shown good performance in solving complex optimization problems. All of these methods are similar in on aspect that the move from one solution to another is done using rules based upon human reasoning, so the called intelligent. Heuristic algorithms may search for a solution only inside a subspace of the total search region. They are not limited by the search space characteristics like existence of derivative of the objective function and continuity.

Several heuristic methods can be addressed such as particle swarm optimization, simulated annealing, Tabu search and genetic algorithms, each one with some advantages and disadvantages in different areas of the problems. These algorithms are generally inspired by modeling the natural processes and other aspects of species evolution, especially human evolution. However, Imperialist Competitive Algorithm has been conceptualized from socio-political evolution of human as a source of inspiration for developing a strong optimization strategy. ICA is a relatively new evolutionary optimization algorithm.

Imperialism is the policy of extending the control of an imperialist beyond its boundaries. It may try to dominate other countries by direct rule or via controlling of markets for goods. ICA is a novel global search heuristic that uses imperialistic competition process as a source of inspiration [21]. This algorithm starts with an initial population (a number of randomly produced solutions). Each solution in the population is called country. Considering the value of objective function as the measure, some of the best countries in the population selected to be the imperialists and the rest form the colonies of these imperialists.

In this algorithm the more powerful imperialist, have more colonies. As the competition starts, imperialists try to achieve more colonies and the colonies start to move toward their imperialists. Therefore, during the competition, the powerful imperialists will be improved and the weak ones will be collapsed. At the end of algorithm just one imperialist will remain. In this stage, the position of imperialist and its colonies will be the same. The algorithm steps are summarized as follows:

Step 1- Generating Initial Empires: The goal of optimization is to find an optimal solution in terms of the variables of the problem. An array of optimization variable values is called 'country'. The cost of a country is found by evaluating the objective function for this country. To start the optimization algorithm we generate the initial population of size $N_{country}$. The N_{imp} of the most powerful countries are selected to form the empires. Other countries will be the colonies each of which belongs to an empire.

Step 2- Moving the Colonies of an Empire toward the Imperialist: Imperialist countries start to improve their colonies. This has been modeled by moving all the colonies in this empire toward the imperialist. It means that a new country will be generated based on the position of each country in the empire and the distance of this country and imperialist.
Step 3- Finding the Total Power of an Empire: The total power of an empire is mostly affected by the power of its imperialist. However, the power of its colonies of an empire has an effect, on the total power of empire. The mean value of the cost function of other countries in the empire will be added to the value of objective function for the imperialistic with a small coefficient to form the power of each empire.
Step 4- Imperialistic Competition: Each empire tries to take the control and ownership of colonies of other empires. This competition brings about a decrease in the power of weaker empires and an increase in the power of more powerful ones slowly. The competition is modeled by choosing a number of weakest colonies of the weakest empires and allows the empires to compete for acquiring the chosen colonies.
Step 5- After a number of iterations only the most powerful empire will remain and this imperialist will control all the countries, which is the optimum solution of the problem.

III. PROPOSED METHOD

The goal of restructuring in power systems is to maximize the social welfare. This objective is satisfied through minimization of the operation and planning costs of the network, while the electric power is delivered to the customers with sufficient reliability. Having a relatively high investment cost, there is considerable risk in DER application. As a result, the optimal placement of these units is a very important optimization problem that should consider various aspects of distribution network. Optimal DER placement and sizing is aimed at maximization or minimization of a specific or combination of objective function considering distribution system constraints [22].

A. The Proposed Method Description

Figure 1 depicts the proposed optimization procedure. Initially the system data and load data at different buses are fed into the optimization algorithm. After that, the optimization problem and algorithm parameters are initialized. Afterward, a Power Flow (PF) is performed for base case (normal condition without DERs) and consequently loss and reliability of the base case of the distribution network are calculated considering the results of this PF.

All of the buses of the system except the reference bus are considered as a candidate location for placement of DERs. Since the DERs are not dispatch able by the Distribution System Operator (DSO), the power production of DER units is considered to be fixed and it can either be zero or full capacity. Empires are initialized in the next step; it should be noted that the size of each solution is equal to the number of buses of the system except the reference bus.

Each solution, therefore, is a matrix that has the size of $1\times(N-1)$ in which N is the number of buses of the system and each column represent the size of DER at that bus. The size of zero indicates that no unit should be installed at that bus. Then a PF is performed for each solution created by the ICA. Using the PF results the costs and benefits of each solution is calculated. In the next step, the colonies of an empire move toward the imperialist. Imperialist countries start to improve their colonies by moving all the colonies within their territory toward the imperialist.

As a result, a new country will be generated based on the position of each country in the empire and the distance of this country and imperialist. If there is a colony in an empire, which has lower cost than the imperialist, it will replace it. Total power of each empire is calculated in the next step. The total power of an empire is affected by the power of its imperialist and the power of its colonies. The mean value of the cost function of other countries in the empire will be added to the value of objective function for the imperialistic with a small coefficient to form the power of each empire.

Afterwards, there will be imperialistic competition in which each empire tries to take the control and ownership of colonies of other empires. This competition brings about a decrease in the power of weaker empires and an increase in the power of more powerful ones slowly. Then empires are checked to determine if there is any empire with no colonies and if there is, that empire will be eliminated. At last, the termination criterion is checked to determine if it is satisfied or not. In this paper, termination criterion is considered to be the number of iterations.

B. Problem Formulation and Objective Function

Considering the load growth with the rate of α, the load associated with the tth year can be calculated using Equation (1).

$$Pd(t) = Pd_B \times (1+\alpha)^{t-1} \quad (1)$$

which Pd_B and $Pd(t)$ denote load at the first and the tth years, respectively.

In the following the proposed approach is explained for placement and sizing of multiple DER units in distribution network. The benefits and costs of DERs application is discussed in the following. DER costs are composed of the investment cost, operation costs, as well as maintenance costs. On the other hand, DER benefits are composed of Power Purchase Reduction (PPR), Loss Reduction (LR), Upgrade Investment Deferral (UID) and Reliability Improvement (RI) as well as Voltage Improvement (VI) of the system as a result of placement of DERs.

C. DER Benefits for the Distribution System

Several benefits of DER application have been considered in this study. Factors such as PPR, LR, UID, RI, and VI are used as terms to study the benefits of DERs implementation. For each year, DER Benefits are calculated. The PPR represents the benefit due to reduction in electric power that must be purchased from electricity market to supply the customers' needs [22].

$$PPR = \sum_{t=1}^{N_{year}} \sum_{k=1}^{N_{DER}} P_{kt}^{DER} \times EP_t \tag{2}$$

where, P_{kt}^{DR} is the output power of the kth DR unit at the tth year and EP_t is the energy price at the tth year. Considering Interest Rate (IR), the value of EP for the tth year can be computed as the following:

$$EP_t = EP_1 \times (1+IR)^{t-1} \tag{3}$$

Reducing the efficiency of transmitting energy to customers significantly, losses in distribution systems draw considerable attention. The total reduction of losses in a distribution system can be calculated as follows:

$$LR = \sum_{t=1}^{N_{year}} (P_{Loss,t} - P_{Loss,t}^{DER}) \times EP_t \tag{4}$$

where, $P_{Loss,t}$ is the power loss before implementation of DER units at the tth year and $P_{Loss,t}^{DER}$ is the total loss after implementation of DER units in the network at the tth year.

As electricity is produced near the loads by DERs, especially during peak load hours, power flows are significantly reduced (as long as the total DER capacity does not exceed the local load), thus deferring the need for upgrading some overloaded feeders [22]. The value of this benefit of DER implementation highly depends on the power system cost-structure, network configuration and planning strategies, type of feeder as well as load growth rate. An annual value of 120 \$/kVA for the deferral benefit is considered for DER application in this study based upon [22, 23].

The DER units can have a positive impact on reliability of the distribution system if they are correctly coordinated with the rest of the network [22]. In this study, it is considered that the DER units can supply all or part of the load in the case of main source unavailability or fault occurrence. Therefore, there will be a reduction of the duration related indices since part of load can be supplied by the DER while the main supply interruption cause is being repaired [24]. Reliability improvement of the system after application of the DER is defined as the following:

$$RI = \sum_{t=1}^{N_{year}} CIC_t - CIC_t^{DER} \tag{5}$$

where, CIC_t is the annual customer interruption cost at year t, without DER application (\$), and CIC_t^{DER} is the annual customer interruption cost when DER is installed in the network at the tth year. The value of loss of load is considered to be 1000 \$/MVA based upon [25].

Implementation of DER units in the distribution system can significantly improve voltage profile of the network. The VI can be the objective of DER application. However since VI is not an economic term it cannot be simply compared with other financial benefits of DER units. Therefore, in this study voltage profile has been considered as a criterion in the simulation. For each possible solution generated by the ICA if the voltage profile is not within the acceptable range a penalty function is considered for that solution. The proposed penalty function considered in this study for contribution of VI in the objective function is formulated in the following.

According to the results of power flow for each solution generated by the ICA, number of violations (n) is determined for each solution of ICA. For these solutions, objective function is calculated as follows [22]:

$$\text{objective function} = Penalty_V \times F \tag{6}$$

$$Penalty_V = \prod_{i=1}^{N_B} Penalty_{V,i} \tag{7}$$

where, F is the primary objective function without consideration of voltage, N_B is the number of buses in the distribution system and the proposed penalty function for each bus, is shown in Figure 1.

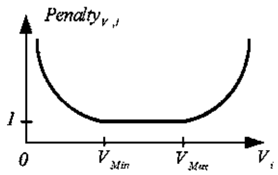

Figure 1. Proposed penalty function [22]

D. DER Costs Calculation

Cost of DER units is composed of three components, investment cost of DER units, operating cost of the DER units, and maintenance cost of DER units. Investment cost includes procurement, installation costs, and costs of required equipment for connection of DER to distribution system. Operating cost is the fuel cost and maintenance cost consists of maintenance and repair costs [22].

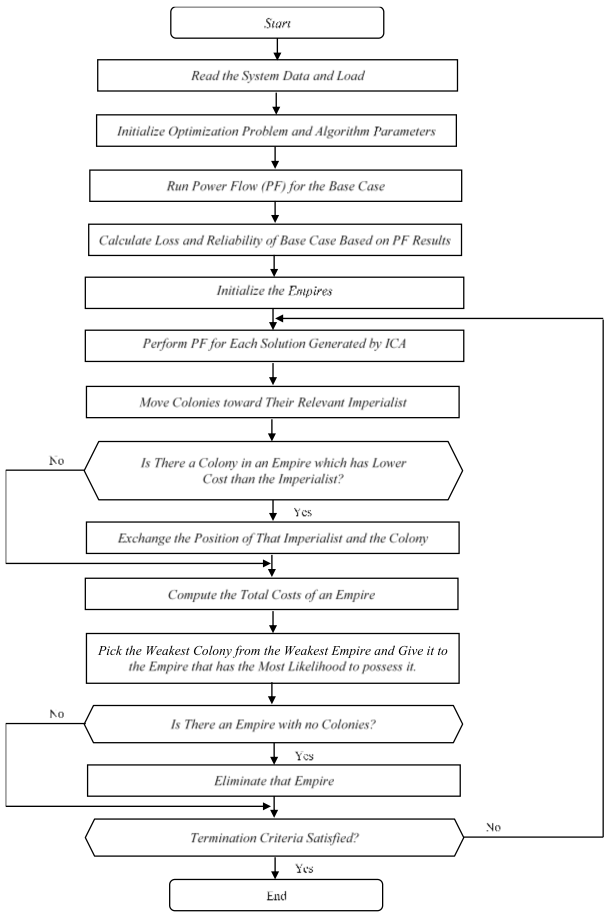

Figure 2. Flowchart of the proposed procedure

IV. CASE STUDIES

The proposed method is tested on the IEEE 30-bus distribution system [26], which is consisted of 1 main feeder and 6 auxiliary substations, and 22 loads. Loading pattern for the base case is provided in Table 1. Active (kW) and reactive (kVAR) loads are for each bus are specified, while the total load is 15 MW. The base apparent power, S is 100 MVA while the base voltage is considered 23 kV. The schematic of the IEEE 30-bus test system is depicted in Figure 3. Table 2 provides the parameters of the HSA and PSO algorithms. Study horizon is considered to be 20 years and IR is 10%.

Table 1. IEEE 30-bus distribution system data

From Bus i	To Bus j	r_{ij} (pu)	x_{ij} (pu)	Base active load at j (MW)	Base reactive load at j (MVAR)
Main Feeder	1	0.0963	0.3219	0	0
1	2	0.0414	0.0022	0.5220	0.1740
2	3	0.0659	0.0651	0	0
3	4	0.2221	0.1931	0.9360	0.3120
4	5	0.1045	0.0909	0	0
5	6	0.3143	0.1770	0	0
6	7	0.2553	0.1438	0	0
7	8	0.2553	0.1438	0	0
8	9	0.2506	0.1412	0.1890	0.0630
9	10	0.2506	0.1412	0	0
10	11	0.7506	0.4229	0.3360	0.1120
11	12	0.3506	0.1975	0.6570	0.2190
12	13	0.1429	0.0805	0.7830	0.2610
13	14	0.2909	0.1639	0.7290	0.2430
8	15	0.0898	0.0781	0.4770	0.1590
15	16	0.1377	0.0775	0.5490	0.1830
16	17	0.2467	0.1390	0.4770	0.1590
6	18	0.0915	0.0795	0.4320	0.1440
18	19	0.3005	0.2612	0.6720	0.2240
19	20	0.2909	0.1639	0.4950	0.1650
6	21	0.1143	0.0994	0.2070	0.0690
3	22	0.1066	0.1054	0.5220	0.1740
22	23	0.0649	0.0641	1.9170	0.0630
23	24	0.1083	0.0941	0	0
24	25	0.2760	0.2399	1.1160	0.3720
25	26	0.2009	0.1746	0.5490	0.1830
26	27	0.2857	0.1609	0.7920	0.2640
1	28	0.0881	0.0047	0.8820	0.2940
28	29	0.3091	0.1741	0.8820	0.2940
29	30	0.2106	0.1187	0.8820	0.2940

Table 2. Parameters of HSA and PSO

Harmony Search Algorithm Parameters					
HMS	HMCR	PAR			$Iter_{max}$
20	0.9	0.35			50
Particle Swarm Optimization Parameters					
Swarm Size	C_1	C_2	W_1	W_2	$Iter_{max}$
30	1.7	1.7	0.8	0.4	150

Two different cases are considered and analyzed in this study. In the first case, the objective of the optimization problem is loss reduction. The second case deals with a multi-objective optimization DR placement problem aimed at the simultaneous reliability improvement, expansion cost reduction, loss minimization and reduction of the power purchased from the electricity power market.

A. Case 1, Multiple-DER Locating for Loss Reduction

In this case, the only objective that is considered in the optimization problem is loss reduction. In order to have a result that is financially reasonable, benefit cost ration (BCR) benchmark is used to evaluate the solutions. Therefore, the objective function is BCR maximization while the only benefit considered are those related to loss reduction. It should be noted that loss at the base case when there is no DER units in the network is 1067.6943 kW/h.

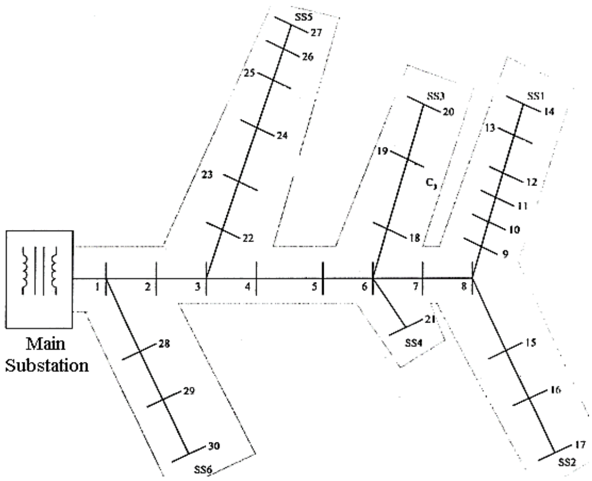

Figure 3. IEEE 30-bus distribution system [26]

Table 3 provides the solution for this case obtained by the ICA. The results obtained by PSO and HSA are also provided in this table. As the results, show the best location for placement of is bus 14 and the optimum size is about 222 kW. As the results demonstrate the ICA yield a better solution comparing other methods. HSA shows better characteristic in this case regarding PSO.

Table 3. The Optimum Solution for the Second Case

Method	DER Location	Size (kW)	*BCR*	Loss Cost Reduction ($)
ICA	14	222.05119	1.2891	117889.2288
PSO	11	223.3239	1.2369	372210.3527
	14	377.0356		
	18	130.2792		
HSA	12	144.2115	1.2781	188197.1178
	14	213.3091		

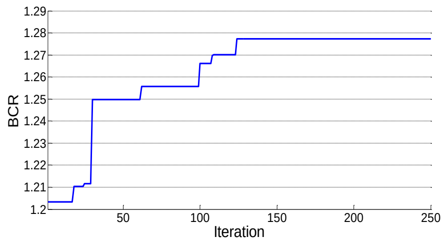

Figure 4. BCR improvement during iterations for case 1

B. Case 2, Multi-Objective Multiple-DER Placement

Conducting a BCR analysis using ICA demonstrate the effects and benefits of DER application on the distribution network. Table 4 shows the optimum size and location of DER units for the ICA. As it can be seen in this table, buses 12 and 14 are the best locations for DER units placement. In order to compare the effectiveness of the ICA with PSO and HSA Table V gives the optimum solution obtained by each method.

As it can be seen the ICA retrieve the best solution that has a higher BCR regarding PSO and HAS. However, the differences are marginal but considering the high value of investment and installation costs even a little increase in the BCR will result in a very high financial saving.

Table 4. The optimum solution obtained by ICA for the case 2

DER Location	Size (kW)	BCR	Loss Cost Reduction ($)	Purchasing Cost Reduction ($)	Interruption Cost Reduction ($)
12	100.1	1.5831	25273	97812	1630.2
14	132.4				

Table 5. Comparison of the best solutions obtained by different methods for case 2

Method	*DER* Location	Size (kW)	BCR	Benefit ($)	Installation and Operation Cost ($)
ICA	12	100.1	1.5831	151672.06	95807
	14	132.4			
PSO	14	500	1.5807	325500	205920
HSA	10	20.2	1.5766	386550.79	245180
	12	75			
	14	500			

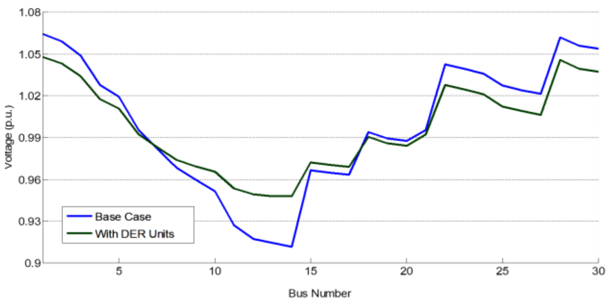

Figure 5. Voltage profile before and after implementation of DER units for the best solution of case 2

C. Discussion

As the results presented in the previous section showed the application of DERs could significantly reduce the loss and operational costs of the system. The obtained results also demonstrate that DER placement is a financially reasonable option that has a BCR over 1.5. On the other hand, the ICA proved that is a very powerful optimization tool, which has advantages over other heuristic method considered here (PSO and HSA). In both cases the results obtained by ICA is better than those obtained by PSO and HSA are. Investigating obtained results show that bus 14 has always been an option for placement of DER units.

As shown in Figure 3 bus 14 has the maximum distance from the substation therefore supplying power to that bus results in the maximum of loss and also voltage reduction. Therefore, bus 14 is a hot spot for implementation of DER units. In order to investigate the influence of DER units implementation on the voltage profile of the distribution network the voltage profile of the system before and after application of the DER units is compared in Figure 5. As shown in this figure the use of DER units has significantly improved the voltage profile of the system.

Bus 14 is the location that is most affected by application of DER units and its voltage has increased considerably. The voltage profile for all buses has improved and the voltage of all buses after implementation of DER units is closer to 1 pu, and the voltage for those buses that were less than one in the base case has increased after DER application and for those that vice versa.

VI. CONCLUSIONS

An efficient method for locating and sizing of multiple DER units in the distribution system was proposed in this paper. The proposed scheme decreases the power losses and power purchased from electricity market, while improves the voltage profile and reduces the system expansion and reinforcement costs. ICA as a novel and powerful optimization method was employed this complicated optimization problem. The results of case studies demonstrate capability of the proposed algorithm in finding the proper location and size of DER units.

The results also demonstrate the advantage of ICA over PSO and HSA in finding the optimum solution. Therefore, the proposed method can be applied by the distribution utilities for DER implementation. As the results demonstrated that with optimal locating and sizing of DER units the BCR can be above 1.5, so this scheme is financially justified.

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