A Multistage Expansion Planning Method for Optimal Substation Placement

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Abstract: The connection points between MV and LV distribution networks are MV substations. Optimal sitting, sizing and timing of MV substation placement is the major planning problem in MV-LV distribution system planning projects. In this paper the optimal MV substation placement problem is solved using Imperialist Competitive Algorithm (ICA) as a new developed heuristic optimization algorithm. This proposed procedure is determined the optimal location, capacity and installation time of MV substation, regarding the operating and optimization constraints. A multistage and pseudo-dynamic expansion planning methodology is applied to consider uncertainties in network parameters such as forecasted load, asset management and geographical constraints. In order to evaluate the efficiency of the proposed method obtained by ICA, a sensitivity analysis for the effect of ICA parameters on obtained results is applied. A graphical representation of results is used to illustrate the efficiency and capability of the procedure both from the planning and graphical aspects. The proposed method has been tested on a real size distribution network.

Keywords: Distribution Substation Allocation, Imperialist Competitive Algorithm (ICA), Load Forecasting, Long-Term Planning.

1 Introduction

The problem of distribution system planning is so complicated that it is usually divided into sub problems. The complexity of optimal distribution system planning is discussed in the literature [1-4]. This problem can be defined in four general steps, namely: Long-term load forecasting, optimal distribution substation placement, optimal HV substation locating and optimal feeder routing. In such approach after long-term load forecasting, the optimization problem of MV substation placement is solved [5].

In the current paper the second stage in distribution systems planning namely optimal MV substation placement is considered. The authors propose the implementation of imperialist competitive algorithm [6] as a new developed optimization tool for the optimal MV substation placement problem. The new algorithm aims to minimize capital investment and operating costs of expanded and new developed installation, considering electrical, geographical and other constraints in optimal distribution substation placement) [5]. The presented model modifies the existing installations and finds the necessary new substations' type, size and location regarding the required future load growth.

There is a set of relevant papers in literature about optimal distribution planning [7-10]. For instance in [10] genetic algorithm and GIS based method is proposed for planning new distribution system in order to increase the serviceability in the distribution system.

In Refs. [11] and [12] a method to increase distribution horizon planning for a 20+ year period is explained. The planning model includes all electric distribution network design requirements for both primary and secondary systems. In Ref. [13] a design optimization model is introduced for distribution substation siting, sizing, and timing. The presented model uses linear functions to express the total cost. A constructive heuristic algorithm to solve DSP problem is proposed by authors of [14]. A local improvement step as well as a branching technique was applied to improve the results. A sensitivity index is applied to add a circuit or a substation to the distribution network.

Authors in [15, 16] presented a model and numerical result for multistage planning of distribution systems with DG. The model involves operational constraints on equipment capacities and voltage limits as well as logical constraints. Computer simulation of the multistage model for distribution expansion design is fully illustrated in [16].

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The uncertainties in distribution system planning especially at the presence of DG, fuel prices, and load growth may increase risks in solving the optimal placement of Distributed Generators (DGs) in distribution system planning. Based on the above uncertainties, authors in [17] proposed the chance constrained programming, which can cover these uncertainties. A Monte Carlo based on GA method is used to solve the developed model. Most of the heuristic search algorithms encounter with some convergence related problems especially in parameter sensitivity to a specific problem. Paper [18] introduces a simple direct method that can reduce the inherent difficulties toward the solution; it can also ensure optimality of the results at the same time. In [19] a multistage distribution system expansion planning procedure is presented. Authors of the paper formulate the investment, operating, and power interruption costs of the system using GA and OPF as an optimization tool. A network configuration optimization method based on Plant Growth Simulation Algorithm, which is relevant to large-scale systems, is presented in [20]. The main merits of the approach compared to previously published random optimization algorithms is that it does not require any external data. The increase in DG connection to the distribution system causes some technical issues in optimal system planning. Paper [21] applies a heuristic approach in order to find optimal DG penetration at distribution system. Distribution system and customer reliability indexes as economic analysis are the major components of distribution system planning. In [22] a comparison of design issues was done to calculate the optimal cable sizing and distribution substation loading. The main contribution of [22] is that while minimizing the total capital cost, the reliability of system improves. A value-based probabilistic approach is used to plan urban electric distribution networks.

In Ref. [23] the application of improved Genetic Algorithm for the optimal design of large scale distribution systems in order to provide optimal sizing and locating of the high voltage substations and medium voltage feeders routing is proposed. In this paper a new concept based on minimum spanning tree is introduced for optimal feeders routing in a real size distribution network.

In Ref. [24] the analysis of cost-effective in-service time periods of indoor and outdoor MV-LV distribution substations operating in Poland is investigated. The method addresses specific components of the overall operating costs, versus in-service time periods depending on a specific accumulation rate, average repair costs and average value of energy not supplied to electricity users following power outage. Paper [25] introduces the possibility of application of u- and k-coefficient to operational reliability analysis of MV-LV transformer-distribution substations. The failure duration index was shown to have specific constraints in cost-related assessments of electric power system reliability. The value of both indices has been determined on the basis of empirical data collected at two major power plants in the period of 10 years.

A simultaneous approach for transmission and substation expansion planning using DC optimal power flow is introduced in [26]. The objectives are to minimize the sum of Investment Costs (IC) and minimize the Expected Operation Costs (EOC). The system load uncertainty has been considered and the corresponding scenarios are generated employing the Monte Carlo (MC) simulation. The merit of the paper is on integrated planning procedure for entire power system. Paper [27] presents a method to design a multi-loop medium voltage network which supplies each MV-LV substation with an alternate feeding point from MV-LV substation to assure the reliability of the system while the total cost of installation, cost of energy losses and cost of unserved energy is minimized subject to operating constraints. In Ref. [28] the optimal expansion of medium-voltage power networks is studied. The paper presents a new hybrid simulated annealing and Tabu search algorithm for distribution network expansion problem. A new methodology using Fuzzy and ABC algorithm for the placement of DG in the radial distribution systems is proposed in [29] to reduce the real power losses and to improve the voltage profile. The proposed method is tested on standard IEEE 33 bus test system and the results are presented and compared with different approaches available in the literature.

Restructuring of power system has faced this industry with numerous uncertainties [30]. As a result, like transmission expansion planning the distribution network planning is very challenging problem.

The electric distribution system Master plan is one of the major projects that can be handling by the application of the proposed method in a multistage and pseudo-dynamic manner.

2 Description of the Optimization

Fig. 1 shows the proposed algorithm [6]. Like other evolutionary methods, the presented algorithm starts with an initial population (countries in the world). Some of the countries in the population are selected to be the imperialists and the rest form the colonies of these imperialists according to a given roles. All the colonies of initial population are divided among the initial imperialists based on their power. The power of an empire is inversely proportional to its cost. After dividing all colonies among imperialists, these colonies start moving toward their relevant imperialist. The total power of an empire depends on not only to the power of the imperialist but also to the power of its colonies. This concept is modeled by a weighted function which includes both the imperialist and its colonies cost.

The next step is the imperialistic competition among all the empires. Empire that is not capability of competition will be eliminated during the competition

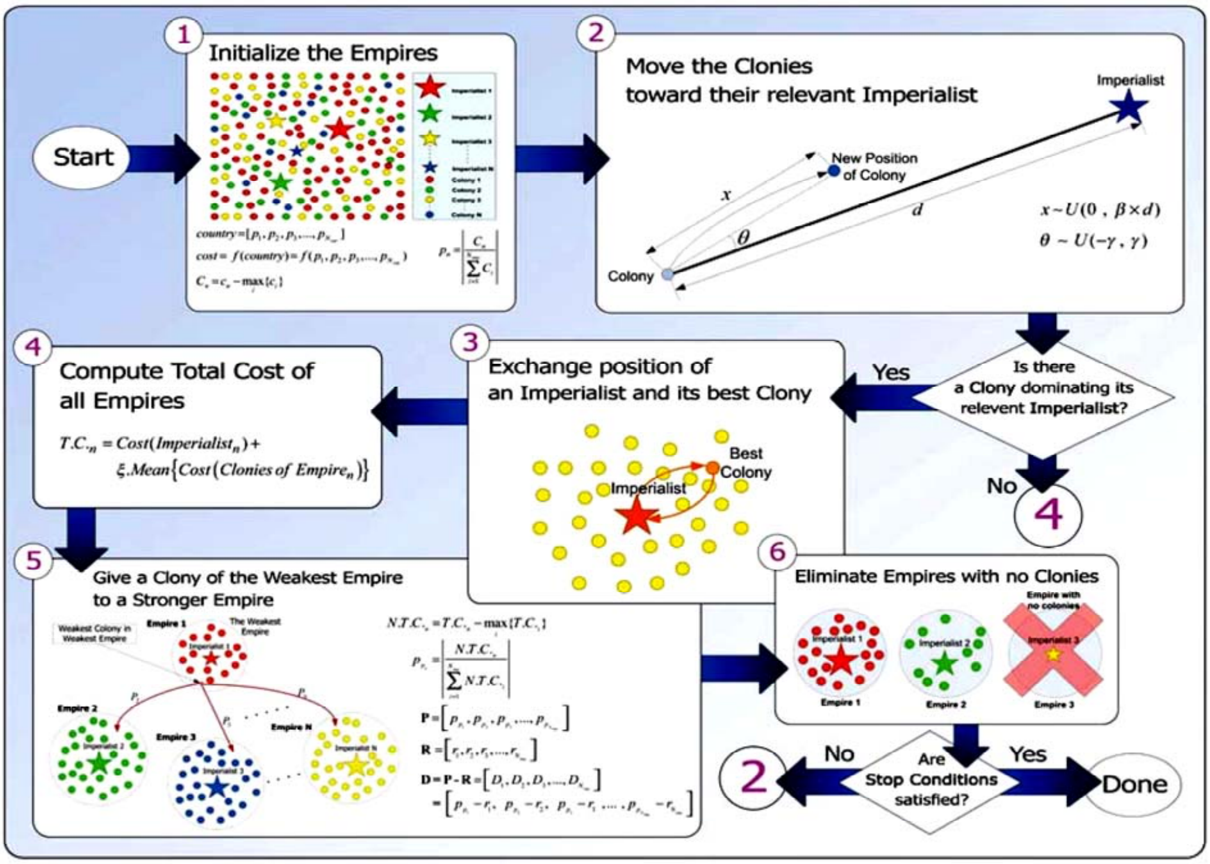

Fig. 1 General representation of ICA [6].

process. In this process the power of powerful empires are expected to increase and the power of weaker ones are decreased. Finally weak empires lose their power and ultimately collapse. The movement of colonies toward their appropriate imperialists during competition process and also the collapse mechanism will cause all the countries to reach to a state that only one empire exist and all the other will be the colonies of that dominant empire. The pseudo code of imperialist competitive algorithm is as follows:

A. Choose some random points on the function and initialize the empires.
B. Move the colonies to their appropriate imperialist for assimilation.
C. Do the revolution process in some colonies by changing the colonies location
D. Exchange the positions of colony by imperialist if has a lower cost than the imperialist.
E. Merge the similar empires.
F. Calculate total cost of empires.
G. Execute the Imperialistic competition procedure by removing the weakest colony from the weakest empires and add it to one of the empires.
H. Delete the weakest empires.
I. *If stop criterion satisfied, end the optimization, else go to B.*

3 Optimal Substation Placement Formulation

The important data for the distribution substation allocation is the peak value and geographical distribution of load in the study area for study year. Moreover, the feasible substation location, considering the geographical limits, is the other one. The load density and its location which is named site is obtained from long-term load forecasting. In current paper the study area of the urban is divided.

The optimal MV substation problem is solved as an optimization problem such that some important constraints are satisfied [1].

- Maximum loading of all MV substations must be satisfied.
- All loads of the system should be supplied.
- The voltage drop should be in acceptable level.
- Total costs of network should be minimum.
- Asset management and geographical constraints should be considered.

Electric distribution system reliability is one of the major planning constraints in distribution system planning. In this paper the above three constraints is checked by the algorithm to consider the reliability of the planned network. Indeed these statements talk about electric distribution network reliability in an indirect manner. The cost function in deregulated environment may be not true. But the aim of this paper is the planning of MV–LV system at conventional electric distribution networks. At such case the only economic player of the system is the electric utility. Hence the energy pricing at any location and time for the study network is a function of system utility. The main topic of this paper is focused on multistage procedure for simultaneous solving of both MV substations placement in conventional large - scale electric distribution networks to address the pseudo-dynamic behavior of the system parameters applying a new introduced optimization algorithm.

Regarding the above constraints, the problem of optimal substation allocation can be formulated as: [1].

$$\begin{aligned} &Minimize \quad Total\,Cost = \sum_{n=1}^{N}\left(CCNS_n + CALS_n\right) + \lambda \sum_{n=1}^{N}\left[\sum_{m=1}^{I_m} IL_{mn}\right] \\ &s.t \quad \sum_{m=1}^{I_m} P_m < S_n ALC\left(S_n\right)\cos\theta \qquad n = 1,2,...,N \\ &\& \quad \sum_{n=1}^{N} I_n = I \quad \& \quad VDI_{mn} < VDI_{\max} \end{aligned} \tag{1}$$

where, the costs function of optimization $IL_{mn} = P_m^2 Dist_{mn}$ is index of low voltage feeder loss of load m supplied from substation *n* where $Dist_{mn}$ is the distance of load m from substation *n* and is defined as Eq. (2).

$$Dist_{mn} = K\,\sqrt{(Dx_m - Dx_n)^2 + (Dy_n - Dy_m)^2} \tag{2}$$

In Eq. (2), (Dx_m, Dy_m) is the center of load point m and (Dx_n, Dy_n) is the location of substation *n*.

$$CALS_n = \lambda\left[P_{NoLoad}\left(S_n\right) + P_{SC}\left(S_n\right)\left(LL\left(S_n\right)\right)^2 ALF\right]T \tag{3}$$

in which $T = T_h * 365 * 24$ is Time in hours ($T_h = 10$ for long-term horizon).

$$LL\left(S_n\right) = \frac{\sum_{m=1}^{I_m} P_m}{S_n \cos\varphi} \tag{4}$$

LL is the percentage of loading of the substation *n*.

$$VDI_{mn} = P_m Dist_{mn} \tag{5}$$

The cost of loss in LV feeder for planning years is given by (6).

$$CostLVF_{mn} = \lambda\left[3\left(\frac{P_m}{3V}\right)^2 Dist_{mn}\, R \;\; ALF\right]T \tag{6}$$

A special load assignment algorithm is developed to consider the following constraints:

- Splitting the study area into square zone named site.
- Load of each site connects to its closest substation.
- Many constraints such as the load value, geographic limitation, substation type and engineering experience should be regarded.

The planning procedure is done first for base case and is extended to long-term period. After base case planning the long-term planning is handled that in which the previously optimal located facilities remain unchanged during long-term study.

For each MV substation, an acceptable feeder length is defined that indeed, checks the voltage drop within the LV feeder. To consider this, an electrical distance is defined between each load and substation as Eq. (7).

$$ED_{mn} = P_m Dist_{mn} < ED_{\max} \tag{7}$$

The $P_m Dist_{mn}$ is voltage drop index of load *m* with respect to substation *n*. This index shows the voltage drops at downstream LV feeders.

The $Dist_{mn}$ obtained from multiplying a factor K to the real distance according to Eq. (8).

$$Dist_{mn} = K\,\sqrt{(Dx_m - Dx_n)^2 + (Dy_n - Dy_m)^2} \tag{8}$$

The ICA is applied to minimizing of objective function which is defined by Eq. (1).

The goal of the optimization process in this step is to determine the best location, size and MV substations, subject to predefined constraints. Each country is defined as a binary vector. The length of the vectors is equal to the number of candidate MV substations, in the feasible topological locations. The feasibility of the geographical constraints is checked by network expert. This is done either by onsite inspection or by GIS system. A selection substation is shown by a binary number, 1. If each variable in each country was “1”, it means that the candidate substation is selected and if the variable in each country was “0”, it indicates that the substation was not selected. The existing substations are set to “1” and are not altered during simulation process. For example, in Fig. 2, there are 14 candidate substations, and some of the selected substations are shown. If the substation No. 13 was an existing substation, its related array in the vector fixes to “1”during simulation. Fig. 2 also shows assimilation procedure which is applied to a hypothetical language characteristic of the country.

Load assignment algorithm is based on minimizing loss and distance. For each load and its substation, a loss index is used. To consider relation of direct and real distance between each load and substation, a correction factor is obtained by statistic sampling of existing LV feeder's length.

There are different types of loads in study area with different load profiles. In an urban electric distribution network design, the load of each site may include different types of the loads for example residential, official, commercial, industrial, and lighting, etc. For each load type there is a different load characteristic such as load factor, load tariffs and penalty factor according to its criticality. If there were different types of loads in a site, its characteristics will be merged.

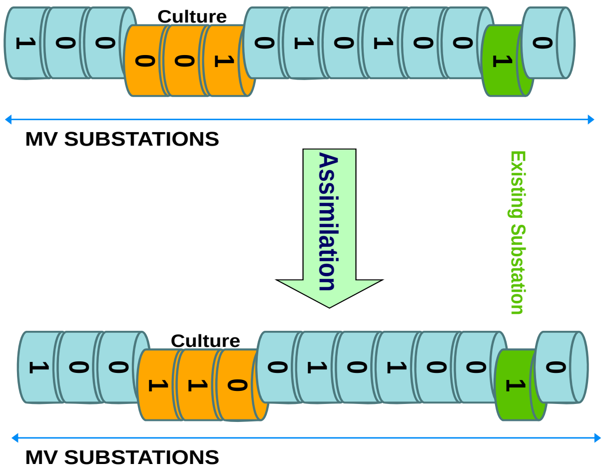

Fig. 2 Design of ICA operator for OSP.

4 Results of Optimal MV Substations Placement

For the evaluation of the performance of the presented algorithm from both the ICA optimization and the substation allocation procedure view a large-scale network is used for simulation. The final goal of optimization is to determine the best places and sizes of a non-given number of substations according to predefined criterion. The studies are performed in a two step namely, base load and long-term load forecasting. The substations which are determined at previously steps are regarded as existing ones, because of the highly cost of removing of an existing substation. On the other hand, it is possible to update its current capacity. In this study, each substation is defined with some parameters: the type, location, rating and date of installation which is determines by ICA. Based on obtained capacity the selected substation may be considered as pole mounted or underground substation. A typical substation loss at its nominal ratings is indicated at Table 1. Besides the candidate MV substation location and initial standard rating is indicated in Table 2. The base load distribution in study area is depicted in Fig. 3 which may be important from load density distribution view in study area. The forecasted peak value of loads (kW) is given in each site. A color representation from white to red spectrum is applied to show the load densities in each site. Sites with higher load value have higher red color.

By knowing that a heuristic method is problem based and it suitability for a given problem does not guarantee that the method is suitable for other. Regarding this it is necessary to examine any specific problem by its own characteristic. Similar to other heuristic optimization algorithms, the obtained results may affected by optimization parameters. To overcome this, a sensitivity analysis is used to adjust the best parameter coefficients for optimal substation problem using ICA. The ICA starts with initial population and the current solutions are updated or changed by optimization parameters of ICA. The number of countries, number of initial imperialists, revolution rate and the assimilation coefficient are the main input parameters in ICA. Table 3 indicates the cost function evaluated using ICA for different country numbers as input variable. At all simulation the iteration counter is set to 100 and the simulation is repeated 20 for the same parameters. The average and best cost with respect to the number of initial countries are compared at this table. Considering of Table 3, while the number of initial country is greater than 50, all of the simulations have the same results as global optimum. There is a relation between number of initial countries and number of initial imperialists. In this paper the best results for two mentioned parameters is suggested as $\frac{N_{Country}}{V_{\mathrm{Im}\,p}} \approx 7$.

The effect of revolution rate on system cost is evaluated and summarized at Table 4. At this stage the number of initial countries is set to 50, and the revolution rate is varied from 0.1 to 1 by step size of o.2. The best result for this variable is given 0.3. To evaluate the effect of assimilation coefficient on system cost a similar method is used. The result for this case is shown in Table 5. From Table 5 it is clear that the best cost is obtained when the assimilation coefficient is set to 0.8.

Table 1 Typical MV substation losses.

MV Substations KVA, Short Circuit and No Load Losses						
KVA	**25**	**50**	**100**	**125**	**200**	**250**
SC Loss [w]	0.75	1.25	2.15	2.5	3.6	4.45
NL Loss [w]	0.15	0.21	0.34	0.4	0.57	0.61
KVA	**400**	**500**	**630**	**800**	**1000**	**1250**
SC Loss [w]	6.45	7.8	9.3	11	13.5	16.4
NL Loss [w]	0.85	1	1.2	1.45	1.75	2.1

Table 2 Candidate MV substations data for base case.

Num	**1**	**2**	**3**	**4**	**5**	**6**
KVA	630	400	315	800	1000	500
X [m]	450	500	600	600	700	700
Y [m]	750	600	750	1000	500	900
Num	**7**	**8**	**9**	**10**	**11**	**12**
KVA	800	100	500	400	315	800
X [m]	750	800	900	900	950	1000
Y [m]	650	1000	550	800	1050	850

Table 3 The average and best cost with respect to the number of initial countries.

Repetition Number = 20		Iteration Number = 100	
Initial Country	**Minimum Cost [$]**	**Average Cost [$]**	**Successful Solution to Global [%]**
10	76360	77232	80
30	76360	77150	96
50	76360	76360	100
100	76360	76360	100

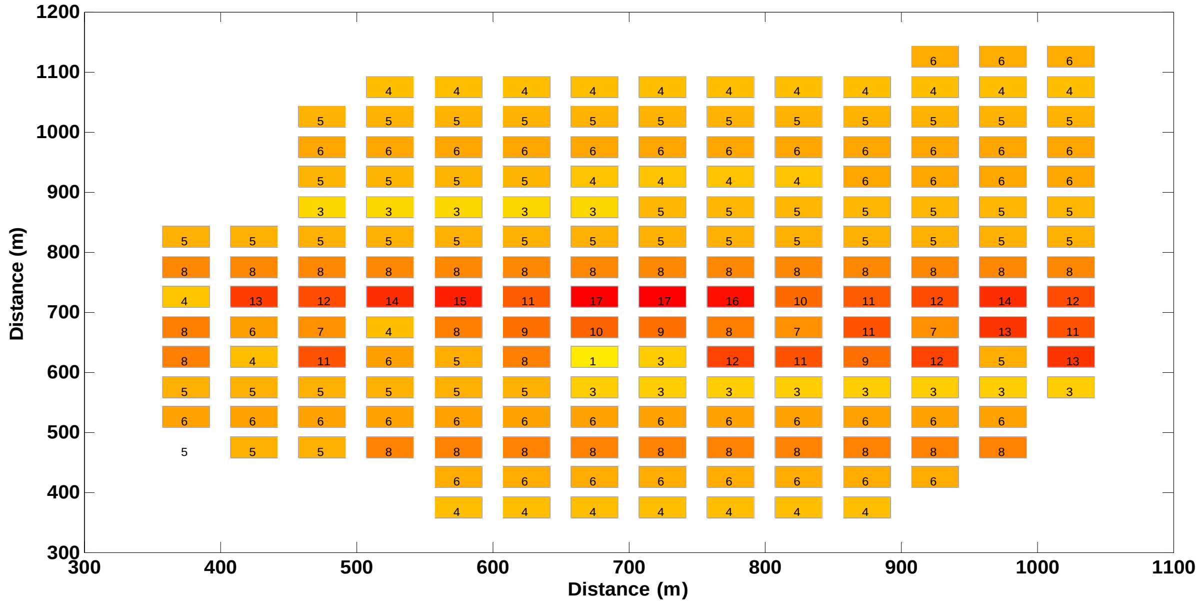

Fig. 3 Peak load distribution on the study area for base case.

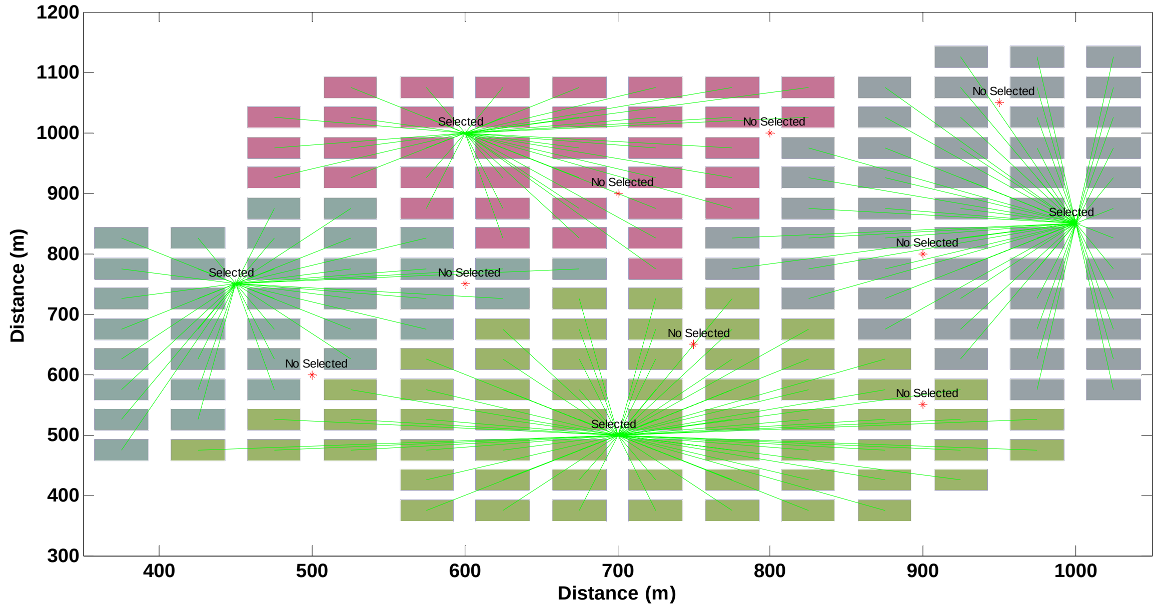

Fig. 4 Optimal substations placement for base case.

Table 4 Effect of revolution rate on system cost.

Initial Country = 50	Repetition Number = 20		Iteration Number = 100
Revolution Rate	**Minimum Cost($)**	**Average Cost($)**	**Successful Solution (%)**
0.1	76532	76843	93%
0.3	76360	76432	100%
0.5	76453	76560	95%
0.7	76782	76983	85%
0.9	76772	77132	80%
1	77012	77472	78%

Table 5 Effect of assimilation coefficient on system cost.

Initial Country = 50	Repetition Number = 20		Iteration Number = 100
Assimilation Coefficient	**Minimum Cost [$]**	**Average Cost [$]**	**Successful Solution to Global [%]**
0.8	76360	76360	100

The results for optimal substation placement in base case satisfying all network constraints, is shown in Fig. 4. Both the location as well as supplied loads of each substation is indicated in this figure. For each selected substation its corresponding supplied area is illustrated with the same color. The center of each site is connected by a LV feeder to its corresponding substation as shown in figure (green lines for new selected substation LV feeders and blue lines for existing substation LV feeders). For each candidate substation there are three terms namely *Exist, Selected* and *No-Selected*. If a substation was in place from the previous planning step this substation is assumed as existing substation and therefore appears as "*Exist*" on the figure. Therefore this substation may be modified to a larger capacity but it is not removed from its current location. A substation that was not selected at the previous step and is chosen in this stage is introduced as a new selected and the term "Selected" will be appear on the figure. On the contrary, if a candidate substation is not selected by the optimization algorithm the title "No-Selected" will appear on the figure. One of the attractive features of the planning tools presented here is its graphical illustration of the results that helps distribution system experts to review the location, size and other data of the planned network. Based on Fig. 4 there are 12 primary candidate substations that at this stage only 4 substations were selected by the ICA. The corresponding loads of each substation are connected through a direct line to own substation.

To confirm the superiority of the presented algorithm, the cost function and the results for base case are compared with a famous and well-designed heuristic method, namely Genetic Algorithm (GA). The given cost by GA and ICA is compared against each other in Fig. 5. The best cost obtained by ICA (dot-line) is smaller than GA (dash-line). Besides the average cost of ICA at the end of simulation process is smaller that shows a better convergence performance. Regarding the figure the ICA has the capability of reaching to global faster than GA in this problem. The best cost that is obtained using GA and ICA is compared in Table 6.

Regarding the results the ICA algorithm gives a better performance with respect to GA both in cost and running time for base case study. To overcome the heuristic algorithm uncertainties and to check the robustness of the solution with acceptable results, the ICA was run many times for this given problem. In any running of ICA with the same data, the same results are obtained and the optimization leads to the same cost value.

To extend the study for long-term planning the simulation is repeated regarding the study area load growth. In this case both the amount of load and the urban geographical expansion are considered. The loads for the study area are shown in Fig. 6. As mentioned before, in this stage the previously selected substations are assumed as existing substations.

The results for long-term system expansion planning are illustrated in Fig. 7. Because of load growth and geographical expansion of the study area, not only some new substations are selected, but also the supplying area of existing substations is modified. Regarding figure, exactly 8 new substations were selected and 4 existing substations are appeared from previous case. Because of the development of the urban, new selected substations are mainly at the around of the study area. The supplied area of existing substation was changed in this case. Because of many uncertainties on urban planning parameters such as lack of master plan, asset management and electric parameters such as load growth, a pseudo-dynamic behavior for long-term planning is mandatory. Hence, the planning procedure must be updated at each given time periods. In this scenario not only the load densities of the study area but also some vacant areas are occupied by new customers. Fig. 7 shows that the study area is extended to east of the city and some new empty areas are occupied with new installations. At the contrary, the center and west of the study area is extended vertically and the load density in this section of the city is increased. It is possible to evaluate the results either by graphical representation or by tabular data. For example the results for substation number 8 are indicated in Table 7. From this table, 11 loads with total value of 55.1 KW is selected to connect to this substation and at the long-term planning horizon, its maximum loading will be 68.8%. The load priority index is shown at last column of Table 7. Load with smaller index is appropriate with smaller loss and voltage drop. The location of substation number 8 is indicated in Fig. 7, at (X, Y) = (800, 1000). Similar tables are used to save the data of substations and loads during simulation process.

Table 6 Comparison of best cost and execution time given by GA and ICA.

Optimization Method	**Best Cost [$]**	**Running Time [sec]**
GA	76899	1402
ICA	76360	1345

Table 7 Substation number 8 load assignment results in long-term planning.

Substation Number = 8		Substation precious Status: Exist	
Substation Load=55.1 kW		Substation Loading=68.8%	
Substation KVA = 100		Substation (X,Y)=(800,1000)	
Number	**Site number**	**Peak load [kW]**	**Load priority index**
1	181	5.02	0.0033
2	182	4.20	0.0011
3	199	5.80	0.0053
4	200	5. 3	0.0028
5	201	4.20	0.0055
6	214	3.97	0.008
7	215	5.79	0.0054
8	216	5.02	0.0033
9	217	4.20	0.0087
10	230	5.80	0.0034
11	231	5.78	0.0092

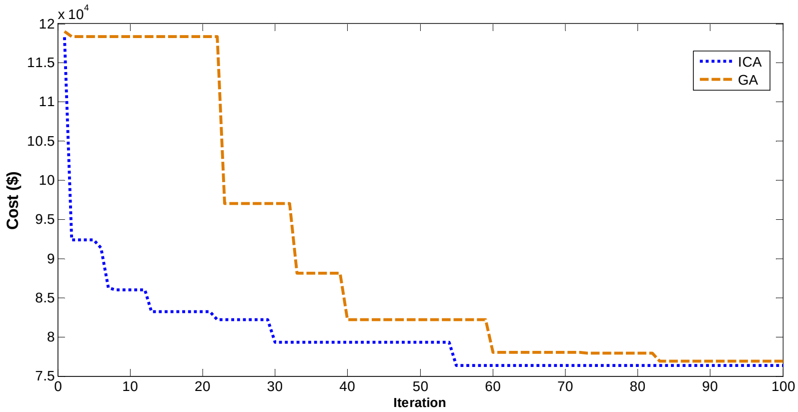

Fig. 5 Best and average cost trace given by GA and ICA for base case.

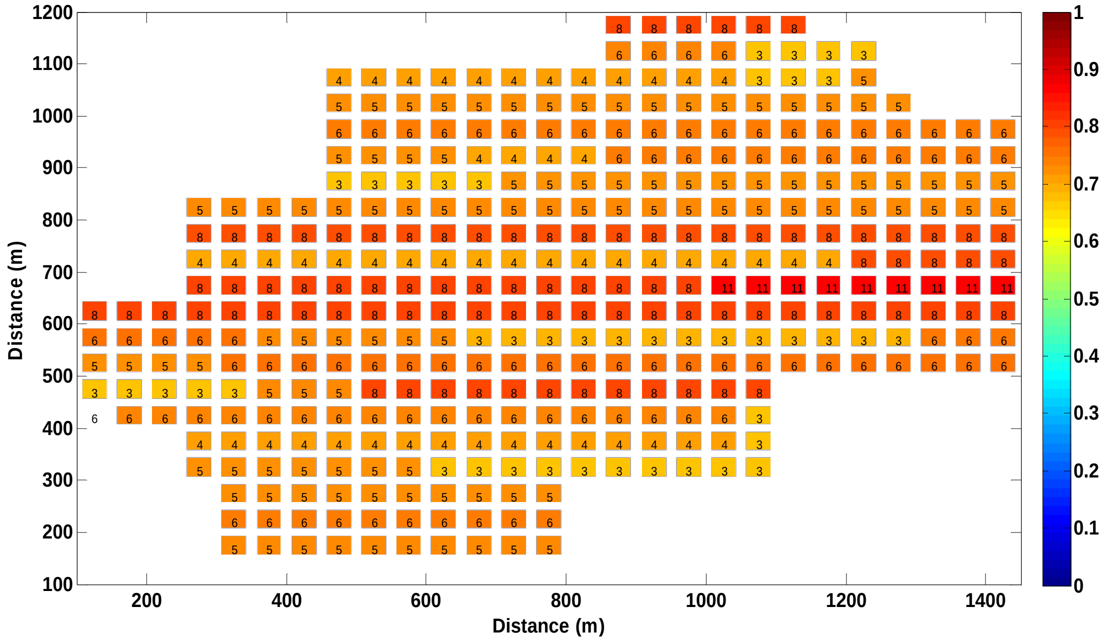

Fig. 6 The load value pattern for the study region in long-term (ten-years) case.

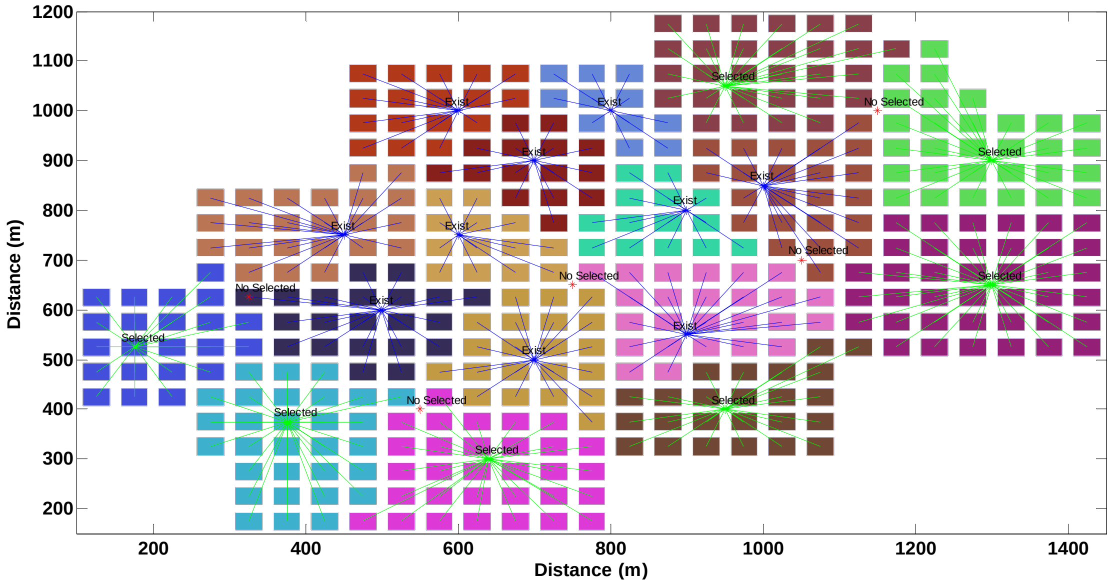

Fig. 7 Optimal substations placement for long-term (ten-years) planning.

5 Conclusion

In this paper a multistage optimal MV substation placement problem is solved by ICA. According to the results the optimal sizing, siting and timing of distribution substation at a pseudo-dynamic planning environment is determined. Some important planning constraints namely electrical, geographical and asset management is formulated as cost function which is optimized by ICA. A new load assignment algorithm is applied for each substation to consider the load connection priority. Simulations started with base case and extended to long-term planning. The results are fully illustrated for two case study both graphically and tabular. To evaluate the effect of optimization parameters on system minimized cost a sensitivity analysis is used. The capability of planning procedure and optimization algorithm is tested on an under developed real size electric power distribution network.

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